HOW WE BECAME HUMAN

SPECIAL EVOLUTION ISSUE

SCIENTIFIC AMERICAN

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SEPTEMBER 2014

The Remarkable 7-Million-Year Story of Us

EVOLUTION
the human saga

INSIDE

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Outcompeting the Rest

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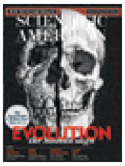

Humans have been evolving for more than seven million years, and we continue to change. This special issue takes stock of the latest insights into that odyssey—past, present and future.

Illustration by Katy Wiedemann.

SCIENTIFIC AMERICAN

September 2014 Volume 311, Number 3

EVOLUTION *the human saga*

INGO ARNDT *Getty Images*

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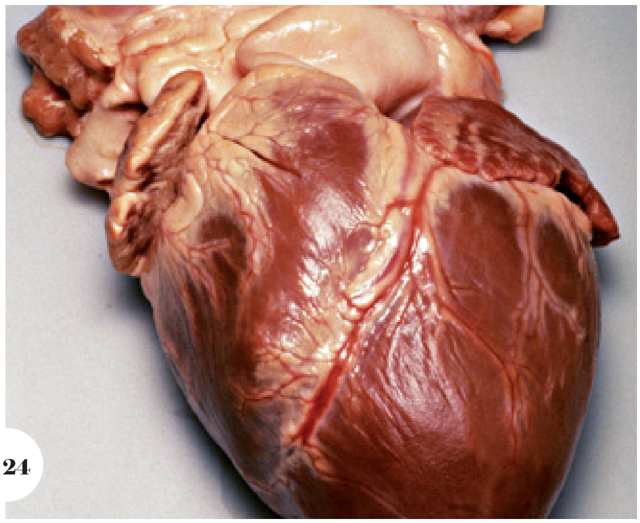

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DEPARTMENTS

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Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

Humanity's Journey

As I type, I am in the cavernlike McCarran Airport in Las Vegas. Frank Sinatra is crooning through the speakers. People are bustling along with their bags, tucking into a sandwich before boarding for their flights and, of course, foolishly dropping their hard-earned money into the ringing, glowing slot machines. I've just come from giving a keynote at the Amaz!ng Meeting, the annual gathering of evidence-based thinkers run by the James Randi Educational Foundation. The irony of the location for such a meeting is not lost on me. At. All.

Not for the first time, I'm marveling at how some seemingly unremarkable primates evolved into an ingenious species displaying a series of similarly fascinating contradictions today. We are clever and silly, poetic and crass, playful and brutal. We contemplate our mortality, selflessly share knowledge with others and consume resources even when we know it's unsustainable.

In every way, we are a remarkable species, but our rise to dominance on this planet was by no means a given. In this, our annual single-topic issue, we explore "The Human Saga" of our species' evolution. The articles probe the narrative arc of human history, from where we began to what the future may hold.

Surely one important key for our success to date is our unique ability to cooperate in large, well-organized groups—at a rate and more expansively than other animals. See "One for All," by primatologist Frans de Waal, starting on page 68.

Today's climate is being influenced by human activity, but perhaps it is a surprise that past rapid swings in climate may have helped shape human adaptability, advances in stone tools and our varied diet, as environmental scientist Peter B. deMenocal describes in "Climate Shocks," beginning on page 48.

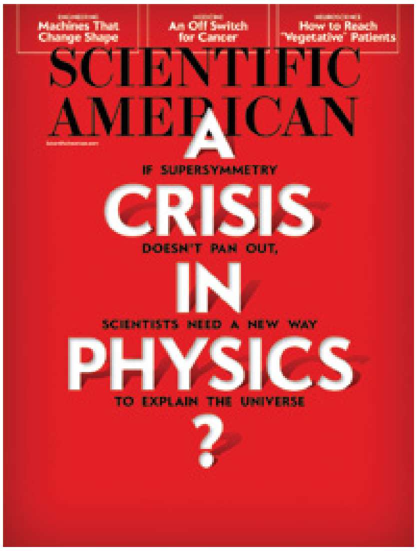
We are not done adapting. Although some believe humans are no longer subject to natural selection, "Still Evolving (After All These Years)," by anthropologist John Hawks, starting on page 86, explains why that is not so. He details why humans actually have evolved rapidly in the past 30,000 years as we have switched from hunting and gathering to agriculture. As we look ahead, we note with no small satisfaction that the human mosaic in all likelihood will only continue to grow more colorful. SA

2014 SCIENCE IN ACTION WINNER

Congrats to Kenneth Shinozuka of Brooklyn, N.Y., winner of the $50,000 *Scientific American* Science in Action prize, part of the Google Science Fair. To protect his beloved grandfather, who suffers from Alzheimer's and is prone to wandering, he paired a wearable foot sensor with a Bluetooth-enabled wireless circuit and a smartphone app. The result can ease the anxieties of families everywhere. Kenneth, a finalist in the 15–16 age category in the Google Science Fair global competition, will join the others at the awards event on September 22 at the company's headquarters in Mountain View, Calif. As chief judge since the fair's founding, I am again looking forward to seeing all the student scientists in action. *—M.D.*

Illustration by Nick Higgins

editors@sciam.com



May 2014

"There are plenty of arguments with which one may oppose capital punishment, but suggesting that lethal injection is as barbarous as gassing or electrocution is unwarranted."

PETER A. BAMBER *MIDGLEY, ENGLAND*

EXECUTION AND ETHICS

In describing the use of an experimental cocktail to execute Dennis McGuire in January as having gone "badly" in "The Myth of the Compassionate Execution" [Science Agenda], the editors say, based on observations by the priest who gave McGuire his last rites, that "McGuire struggled and gasped for air for 11 minutes, his strained breaths fading into small puffs" before he died 26 minutes after the injection. As a practicing anesthesiologist, I conclude from this description that McGuire's priest probably witnessed the effects of airway obstruction in an unconscious but not yet dead subject, which may have been upsetting to the priest but would have been of no consequence to McGuire.

There are a variety of drugs that cause rapid loss of consciousness. In contrast, lethal gassing will often bring on distressing breathlessness before permanent loss of consciousness, and death by electrocution may cause extreme pain. There are plenty of arguments with which one may (and personally I think should) oppose capital punishment, but to oppose it by suggesting that lethal injection is as barbarous as gassing or electrocution is unwarranted.

Peter A. Bamber
Midgley, England

I would argue that there is a moral imperative for medicine to work on perfecting a hasty and painless death. While doctor-assisted suicides do not and should not involve healthy people, even a terminally ill patient's body can put up a significant struggle to live under the effects of adrenaline and the emotions related to death. Although the method of administration in doctor-assisted suicides and executions may need to differ, it seems that the desired result in both cases would be the same: a respectful death.

Talon Swanson
Seattle

While I endorse this article's opinions and am opposed to the death penalty, I must disagree with the editors' statement that "scientific protocols for executions cannot be established, because killing animal subjects for no reason other than to see what kills them best would clearly be unethical." In the veterinary world, animal euthanasia is sadly performed many times a day, for many reasons.

Some years ago after fighting all day for the life of my horse, Alex, I took him to our local surgeon. It turned out he had colic. We led him into my trailer, where he was given a barbiturate, and he died without a twitch. The mercy we give to our animals and pets is the heavy price we pay for their love and companionship.

Chris Stross
via e-mail

SUPERSYMMETRY PREDICTION

In "Supersymmetry and the Crisis in Physics," Joseph Lykken and Maria Spiropulu discuss hopes that evidence of supersymmetry, which proposes that all known particles have hidden superpartners, will be found at CERN's Large Hadron Collider within a year's time—and the effects on physics as a whole if it is not.

There is one approach to superpartner discovery that the authors do not explore. Many people think the framework of string theory and its M-theory variant, with small extra dimensions, is well motivated. To make predictions from the 10- or 11-dimensional string/M theories, it is necessary to project them onto a world with four spacetime dimensions, and some resulting descriptions have had phenomenological successes. Essentially all predict that some superpartners of the electroweak gauge bosons will be light enough to observe at the LHC after its upgrade. Some also predict that gluinos, the proposed superpartners of gluons, will be light enough to observe there.

Predictions based on such theories should be taken seriously. I would like to bet that some superpartners will be found at the LHC, but I have trouble finding people who will bet against that prediction.

Gordon Kane
Victor Weisskopf Distinguished University Professor of Physics
University of Michigan

Lykken and Spiropulu write about a crisis in physics that results if we fail to discover supersymmetry. But they and the editors of *Scientific American* have neglected possibilities that I reported on in your own blogosphere in 2012 (ScientificAmerican.com/sep2014/beyond-higgs): that there is nothing whatsoever wrong with the Standard Model, that it doesn't need fixing and that even adding quantum gravity may not spoil it. That scenario is more boring than all the wonderful ideas being put forward but is much simpler.

Glenn D. Starkman
Professor of Physics and Astronomy
Case Western Reserve University

SECONDHAND VAPOR

In "Are E-Cigarettes Safe?" [The Science of Health], Dina Fine Maron notes that one of the concerns about e-cigarettes is that they expose users and bystanders to "unidentified dangers."

As a bystander, I am concerned about

being exposed to both unidentified dangers and identified vapors that I do not want to breathe. Many public places that have set aside smoking areas do not know what to do with e-cigarette users. Society needs to separate all smoke and vapor users from nonusers in such spaces.

Mathieu Federspiel
via e-mail

MATH PRODIGIES

In reading the story of mathematics prodigy Srinivasa Ramanujan, who died at 32, in "The Oracle," by Ariel Bleicher, I am reminded of another self-taught, towering mathematical genius: Frenchman Évariste Galois, who died in a duel at age 20. He developed the basis of group theory a generation ahead of his time. The works of both these great intellects continue to be mined generations later for remarkable insights.

David Howell
via e-mail

BAFFLING BOTTLE

"Shape-Shifting Things to Come," by Sridhar Kota, cites shampoo bottle caps as an example of the engineering approach of compliant design, in which flexible mechanisms are made with the fewest possible parts. Now I know who to blame for caps whose hinge breaks when dropped, whose nozzle clogs, and which are impossible to get off and replace when extracting the last 20 percent of the contents.

Roger Friedman
via e-mail

HIDDEN CONSCIOUSNESS

Adrian M. Owen's article on imaging techniques developed to determine when seemingly vegetative patients are actually conscious ["Is Anybody in There?"] caused me to wonder about the described patients after they no longer had access to the equipment and technicians. Having myself spent weeks on life support in a pulmonary intensive care unit, though always conscious, I know that an inability to communicate is immensely frustrating. The index cards and pens provided by my sister as a means of communication were greatly valued. I hope that some means was found to continue communicating with the patients.

Mark Virovatz
Houston

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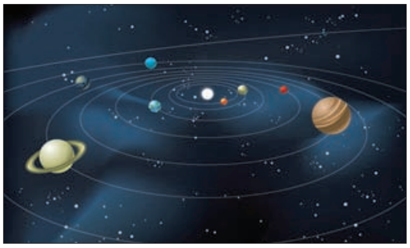
view the sea? We'll focus on Maya culture and the sea as seen in painted pottery, monumental sculpture, and colonial-era narratives.

Maya Pilgrimage to Ritual Landscapes

Recent archaeological and anthropological findings have shed new light on ancient Maya travel, religion, and views of the landscape. Islands, mountains, caves, and lakes made up sacred places to them. This session looks at the latest interpretations of ancient Maya pilgrimage, their ritual landscapes, and how these were central to Maya society.



Our Solar System

Speaker: Adriana C. Ocampo, Ph.D.

Cosmic Collision: The Search for the Dinosaur Killer

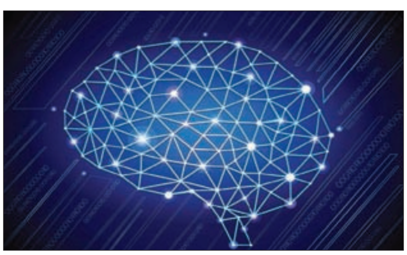
Around 65 million years ago a massive space rock hit Central America, setting off a biospheric disaster that wiped out the dinosaurs. Take a voyage back in time, via Belize and neighboring Mexico, to explore the impact site of the ancient asteroid that drastically altered the balance of life on Earth.

Our Neighborhood in the Solar System

In this extraordinary time for planetary science we are beginning to understand planetary formation processes that were wholly unknown to us just a short time ago. Guided by the latest scientific insights, we'll discuss how planets form, why asteroids and comets are important, and whether habitable environments exist beyond Earth.

Exploring our Solar System

NASA's robots have now taken us out to 180 astronomical units (AU), or about 180 times the distance from Earth to the Sun. We'll delve into some of their fascinating discoveries, such as the similarities and differences between the gas giant planets and the key role Jupiter plays for Earth.



Neuroscience

Speaker: Lary C. Walker, Ph.D.

Life and its Discontents

Disease is an inescapable fact of life, but our very existence is shaped by our relationship with potential disease agents. We'll explore the biological origins of disease to understand why the brain is vulnerable to a distinctive constellation of disorders as we age.

Scratching Sheep, Mad Cows, and Laughing Death

Follow the incredible scientific odyssey that began in the 18th century with a mysterious disease of sheep and, in the 20th century, bore two Nobel Prizes. Learn about the prion, an infectious protein and possibly the most controversial molecule in the history of medicine.

Why Old Brains Falter

One of the most feared diseases of old age is Alzheimer's disease, the most frequent cause of dementia. Learn how the brain changes in normal aging and in Alzheimer's disease, how Alzheimer's emerges and spreads within the brain, and why it is so difficult to stop.

Alzheimer's Therapies: Hype and Hope

No current treatment can stop the relentless progression of Alzheimer's disease. We'll explore the history of rational therapeutic approaches to Alzheimer's and take a frank look at the benefits and shortcomings of existing treatments. Finally, we'll consider how our growing knowledge of brain aging offers hope that an effective therapy is possible.

SCIENTIFIC AMERICAN Travel HIGHLIGHTS OUTER SPACE AND OPEN SPACE IN FLORIDA

BOK TOWER GARDENS: Sunday, March 22, 11am – 4pm

KENNEDY SPACE CENTER (KSC): Monday, March 23, 8am – 7:30pm

Continue the Bright Horizons fun with a two-day exploration of two very different central Florida gems: Bok Tower Gardens and Kennedy Space Center.

Bok Tower Gardens — a National Historic Landmark botanical garden and bird sanctuary — is an opportunity to relax amidst subtropical landscape gardens which help preserve 64 rare Central and North Florida plant species. We'll also hear the Garden's 60-bell carillon play.

Reconnect with the spirit and substance of space exploration on our visit to Kennedy Space Center. Guided by tour specialists, explore the world's largest launch facility.

First stop: Launch Control Center. Journey inside the firing room where the last 21 shuttle launches were controlled. Pass by the computer consoles at which engineers constantly monitored the launch controls. See the launch countdown clock and large video monitors on the walls. Enter the bubble room with its wall of interior windows through which the management team viewed all of the proceedings below. Re-live the last shuttle launch, Atlantis mission STS-135 (see takeoff photo, below), while watching the launch footage in the room where the launch became part of history.

Get the right stuff at lunch as we meet a veteran member of NASA's Astronaut Corps, have a hot buffet lunch, and participate in a 30-minute interactive Q&A during "Lunch with an Astronaut."

Onward to the Space Shuttle Atlantis, along with the interactive exhibits that bring to life the complex story of the shuttle and the thousands of people who created and maintained it.

Join us for a memorable look at KSC's role in the endeavor of exploration.

Price: $899 per person, based on double occupancy; $1,399 for a single. Kennedy Space Center launch facilities are transitioning to commercial missions and are under construction. Therefore the structures and vantage points we experience and the entire sequence of our day are subject to change. Regardless of our tour route, we will have an excellent tour of KSC!

Free Up the Two-Year Colleges

To bolster the nation's high-tech labor pool, some higher education should come without a tuition bill

Tennessee does not immediately come to mind as a progressive force in science and technical education. Even today the legacy of the infamous 1925 Scopes trial persists: a relatively new state law invites teachers to criticize mainstream science, be it evolution or global warming.

Yet the antediluvian "Monkey Bill," as opponents call the 2012 legislation, has not prevented the state from taking the national spotlight as an educational innovator. In May, Republican governor Bill Haslam signed a bill that will make Tennessee's two-year community colleges and technical schools free to any high school graduate starting in 2015.

Community colleges are pillars of STEM (science, technology, engineering and mathematics) education. They train technicians for jobs in leading-edge industries and grant associate's degrees that let students finish the last half of their higher education at a four-year institution. While the gap in economic well-being between college graduates and those with only a high school diploma grows ever wider, community colleges serve as gateways for the underrepresented and the working class. Nationwide, 40 percent of community college students are in the first generation of their families to attend college, more than 55 percent of Hispanics in college are enrolled in community colleges, and 40 percent of community college students hold down full-time jobs.

The National Science Foundation has long recognized the importance of two-year schools as training grounds for high-tech industries such as biotechnology and nanotechnology. It devotes more than $60 million annually to its Advanced Technological Education program, which develops curricula to immerse students, for instance, in the nuances of cell cultures and standard deviations. Graduates of these courses go on to careers in the laboratories of Genentech and the command centers of nuclear power plants. Veterans returning to the workforce receive training for technical careers in the aerospace industry.

The Tennessee law will enable students to attend the state's 13 community colleges and 27 technical schools tuition-free in hopes of raising the number of college graduates in the state from 32 to 55 percent by 2025. (The national average is now 42 percent.) The program will be funded largely by lottery money and will also somewhat reduce scholarships at the state's four-year institutions. If a trade-off has to be made, this one may be worth it to upgrade a workforce judged in one survey to be of low quality. Other states—and the private sector—are watching closely. Oregon has plans to make community college free, and Mississippi may try again after the death of a bill this year. These efforts should be viewed as models for other states to emulate. To succeed, though, the two-year schools will need a lot of help.

Community colleges have long wrestled with the responsibility of having to offer remedial education for entrants who arrive at their doors without a proper grounding in basic skills. The educational deficits are one reason only 32 percent of Tennessee's students finish at state-run community colleges, which is why Haslam's program appoints "mentors" to ease the transition.

To ensure that the newly enrolled reach graduation day, administrators of community colleges must emphasize accelerated remedial programs to get students through the basics and into career-related classes quickly enough to avoid the frustration and despondency that lead to elevated dropout rates.

The two-year colleges should also give serious consideration to new teaching methods that could maximize the time teachers have to interact with their students. Bill Gates, whose foundation has contributed tens of millions to remedy the failings of two-year schools, recommended in a speech last year that community colleges experiment with "flipped classrooms." Students watch lectures from MOOCs (massive open online courses) at home. In class, instead of getting lectures, they complete homeworklike exercises, with personalized instruction from professors and teaching assistants.

Two-year college students face an obstacle course of personal and academic challenges on the path to a diploma. Many must hold down a job or two while attending courses. The renewed spotlight on community colleges is essential for transforming these vital institutions into gateways to the tech-oriented skills that serve as the foundation for vibrant economies. SA

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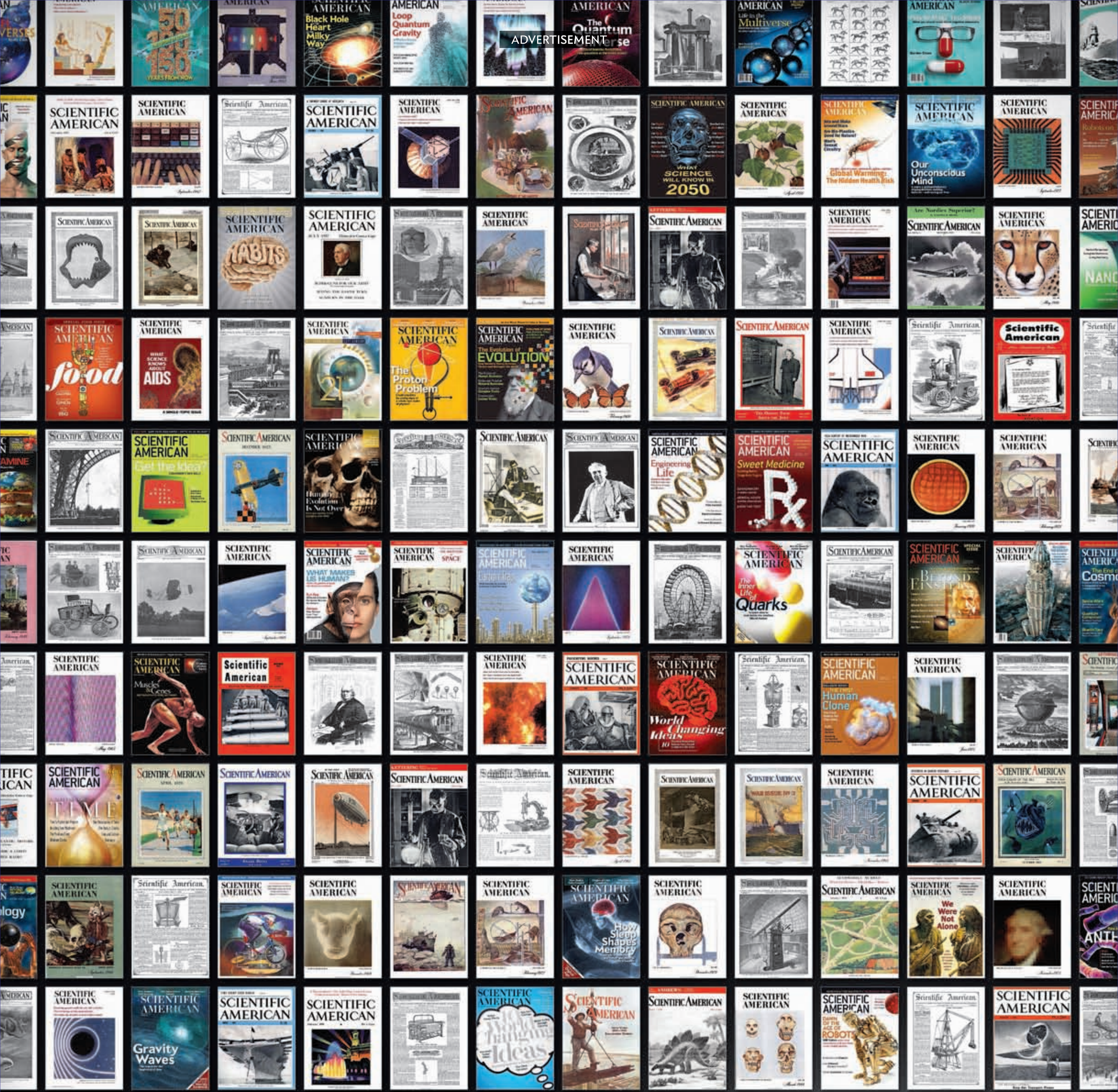
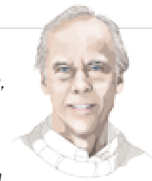
Illustration by Ross MacDonald



SCIENTIFIC AMERICAN
The Proton Problem

Commentary on science in the news from the experts

R. Douglas Fields is a neuroscientist in Bethesda, Md., and author of *The Other Brain,* a book about glia, which constitute the majority of cells in the brain and communicate without using electricity. He serves on the board of advisers for *Scientific American Mind.*



Vive la Différence

Requiring medical researchers to test males and females in every experiment sounds reasonable, but it is a bad idea

Sex differences lie at the core of biology. They are the driving force of evolution, and in many cases they are fundamental in health and medicine. The study of sex differences is important work, and more of it should be done. But a new National Institutes of Health policy intended to drive research in sex differences is a major step in the wrong direction.

The policy, which requires NIH-funded scientists to use equal numbers of male and female animals and cells in their studies, is about politics, not science. In January, Representatives Nita Lowey of New York and Rosa DeLauro of Connecticut wrote to Francis Collins, director of the NIH, expressing concern that women's health was being put at risk because biomedical researchers often prefer to use male animals for experiments. Apparently their message came through clearly. In May, Collins and Janine Clayton, associate director for Research on Women's Health at the NIH, announced in *Nature* that in all experiments funded by the agency, scientists must use equal numbers of male and female animals or cells and investigate the differences by sex. This directive will affect nearly every researcher. "The exception will be truly an exception, not the rule," Clayton stated at a press conference. (*Scientific American* is part of Nature Publishing Group.)

On the surface, this rule sounds reasonable enough. Why not include males and females in every study? In fact, the rule would be a huge waste of resources.

Say a scientist wants to test a blood pressure drug. One group of lab rats (the experimental group) is treated with the new compound, and the other (the control group) receives sugar pills. After treatment, researchers measure the mean blood pressure in both groups as well as the amount of variation surrounding each mean. The variation around the mean, usually a bell-shaped distribution, is important. The more variation in the results, the harder it is to conclude that any differences between the control and experimental groups are meaningful. Scientists therefore take great care to minimize the amount of variation—for example, by using only specific purebred lines of animals of the same age and often the same sex (male or female, depending on which sex minimizes variance in the particular experiment).

If scientists must add a second factor—sex—to their experiment, two things happen: the sample size is cut in half, and variation increases. Both reduce the researchers' ability to detect differences between the experimental and control groups. One reason variation increases is the simple fact that males and females are different; these differences increase the range of scores, just as they would if males and females competed together in Olympic weight lifting. The result is that when males and females are mixed together, scientists might fail to detect the beneficial effect of a drug—say, one that reduces blood pressure in males and females equally well.

In their *Nature* commentary, the NIH officials argue that scientists exclude females by "convention" or to avoid variability caused by hormonal cycles in females. This is not accurate. Scientists have enormous practical and financial incentives to use both sexes of animals in their studies: doing so cuts animal costs in half. Transgenic animals in particular are rare, are difficult to breed and can cost thousands of dollars apiece. As a consequence, scientists exclude one sex from a study when it is necessary—when there is reason to suspect that the results will differ between sexes, possibly for trivial causes, such as if a male rat might run a maze faster than a female.

It is critical to understand biological differences between the sexes. But understanding sex differences is much more complex than the NIH mandate would suggest. Modifying experiments to include both males and females costs money and requires a duplication of time and effort—time that researchers might not have to spare or that might be better spent conducting other research—that is rarely practical or scientifically warranted. A much better way is to fund opportunities specifically designed to study sex differences. If the NIH makes sex research a priority and earmarks money to support it, scientists will apply. For precedent, look to the Obama administration's recent projected $4.5-billion BRAIN Initiative, which has unleashed a flood of brain research. The new mandate does just the opposite: it compels all researchers to study sex regardless of the objective of their study, and it provides no additional funding to do so. SA

SCIENTIFIC AMERICAN ONLINE
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Illustration by Scott Brundage

For people with a higher risk of stroke due to Atrial Fibrillation (AFib) not caused by a heart valve problem

ELIQUIS® (apixaban) is a prescription medicine used to reduce the risk of stroke and blood clots in people who have atrial fibrillation, a type of irregular heartbeat, not caused by a heart valve problem.

IMPORTANT SAFETY INFORMATION:

- **Do not stop taking ELIQUIS for atrial fibrillation without talking to the doctor who prescribed it for you. Stopping ELIQUIS increases your risk of having a stroke.** ELIQUIS may need to be stopped, prior to surgery or a medical or dental procedure. Your doctor will tell you when you should stop taking ELIQUIS and when you may start taking it again. If you have to stop taking ELIQUIS, your doctor may prescribe another medicine to help prevent a blood clot from forming.
- **ELIQUIS can cause bleeding, which can be serious,** and rarely may lead to death.
- **You may have a higher risk of bleeding if you take ELIQUIS and** take other medicines that increase your risk of bleeding, such as aspirin, NSAIDs, warfarin (COUMADIN®), heparin, SSRIs or SNRIs, and other blood thinners. **Tell your doctor about all medicines, vitamins and supplements you take.** While taking ELIQUIS, you may bruise more easily and it may take longer than usual for any bleeding to stop.
- Get medical help right away if you have any of these signs or symptoms of bleeding:
  - unexpected bleeding, or bleeding that lasts a long time, such as unusual bleeding from the gums; nosebleeds that happen often, or menstrual or vaginal bleeding that is heavier than normal
  - bleeding that is severe or you cannot control
  - red, pink, or brown urine; red or black stools (looks like tar)
  - coughing up or vomiting blood or vomit that looks like coffee grounds
  - unexpected pain, swelling, or joint pain; headaches, feeling dizzy or weak
- **ELIQUIS is not for patients with artificial heart valves.**
- **Spinal or epidural blood clots or bleeding (hematoma).** People who take ELIQUIS, and have medicine injected into their spinal and epidural area, or have a spinal puncture have a risk of forming a blood clot that can cause long-term or permanent loss of the ability to move (paralysis).

IMPORTANT FACTS about ELIQUIS® (apixaban) tablets

℞ ONLY

The information below does not take the place of talking with your healthcare professional. Only your healthcare professional knows the specifics of your condition and how ELIQUIS may fit into your overall therapy. Talk to your healthcare professional if you have any questions about ELIQUIS (pronounced ELL eh kwiss).

What is the most important information I should know about ELIQUIS (apixaban)?

For people taking ELIQUIS for atrial fibrillation: Do not stop taking ELIQUIS without talking to the doctor who prescribed it for you. Stopping ELIQUIS increases your risk of having a stroke. ELIQUIS may need to be stopped, prior to surgery or a medical or dental procedure. Your doctor will tell you when you should stop taking ELIQUIS and when you may start taking it again. If you have to stop taking ELIQUIS, your doctor may prescribe another medicine to help prevent a blood clot from forming.

ELIQUIS can cause bleeding which can be serious, and rarely may lead to death. This is because ELIQUIS is a blood thinner medicine that reduces blood clotting.

You may have a higher risk of bleeding if you take ELIQUIS and take other medicines that increase your risk of bleeding, such as aspirin, nonsteroidal anti-inflammatory drugs (called NSAIDs), warfarin (COUMADIN®), heparin, selective serotonin reuptake inhibitors (SSRIs) or serotonin norepinephrine reuptake inhibitors (SNRIs), and other medicines to help prevent or treat blood clots.

Tell your doctor if you take any of these medicines. Ask your doctor or pharmacist if you are not sure if your medicine is one listed above.

While taking ELIQUIS:

- you may bruise more easily
- it may take longer than usual for any bleeding to stop

Call your doctor or get medical help right away if you have any of these signs or symptoms of bleeding when taking ELIQUIS:

- unexpected bleeding, or bleeding that lasts a long time, such as:
  - unusual bleeding from the gums
  - nosebleeds that happen often
  - menstrual bleeding or vaginal bleeding that is heavier than normal
- bleeding that is severe or you cannot control
- red, pink, or brown urine
- red or black stools (looks like tar)
- cough up blood or blood clots
- vomit blood or your vomit looks like coffee grounds
- unexpected pain, swelling, or joint pain
- headaches, feeling dizzy or weak

ELIQUIS (apixaban) is not for patients with artificial heart valves.

Spinal or epidural blood clots or bleeding (hematoma). People who take a blood thinner medicine (anticoagulant) like ELIQUIS, and have medicine injected into their spinal and epidural area, or have a spinal puncture have a risk of forming a blood clot that can cause long-term or permanent loss of the ability to move (paralysis). Your risk of developing a spinal or epidural blood clot is higher if:

- a thin tube called an epidural catheter is placed in your back to give you certain medicine
- you take NSAIDs or a medicine to prevent blood from clotting
- you have a history of difficult or repeated epidural or spinal punctures
- you have a history of problems with your spine or have had surgery on your spine

If you take ELIQUIS and receive spinal anesthesia or have a spinal puncture, your doctor should watch you closely for symptoms of spinal or epidural blood clots or bleeding. Tell your doctor right away if you have tingling, numbness, or muscle weakness, especially in your legs and feet.

What is ELIQUIS?

ELIQUIS is a prescription medicine used to:

- reduce the risk of stroke and blood clots in people who have atrial fibrillation.
- reduce the risk of forming a blood clot in the legs and lungs of people who have just had hip or knee replacement surgery.

It is not known if ELIQUIS is safe and effective in children.

Who should not take ELIQUIS (apixaban)?

Do not take ELIQUIS if you:

- currently have certain types of abnormal bleeding
- have had a serious allergic reaction to ELIQUIS. Ask your doctor if you are not sure

What should I tell my doctor before taking ELIQUIS?

Before you take ELIQUIS, tell your doctor if you:

- have kidney or liver problems
- have any other medical condition
- have ever had bleeding problems
- are pregnant or plan to become pregnant. It is not known if ELIQUIS will harm your unborn baby
- are breastfeeding or plan to breastfeed. It is not known if ELIQUIS passes into your breast milk. You and your doctor should decide if you will take ELIQUIS or breastfeed. You should not do both

Tell all of your doctors and dentists that you are taking ELIQUIS. They should talk to the doctor who prescribed ELIQUIS for you, before you have **any** surgery, medical or dental procedure. **Tell your doctor about all the medicines you take, including** prescription and over-the-counter medicines, vitamins, and herbal supplements. Some of your other medicines may affect the way ELIQUIS works. Certain medicines may increase your risk of bleeding or stroke when taken with ELIQUIS.

How should I take ELIQUIS?

Take ELIQUIS exactly as prescribed by your doctor. Take ELIQUIS twice every day with or without food, and do not change your dose or stop taking it unless your doctor tells you to. If you miss a dose of ELIQUIS, take it as soon as you remember, and do not take more than one dose at the same time. **Do not run out of ELIQUIS (apixaban). Refill your prescription before you run out.** When leaving the hospital following hip or knee replacement, be sure that you will have ELIQUIS available to avoid missing any doses. **If you are taking ELIQUIS for atrial fibrillation, stopping ELIQUIS may increase your risk of having a stroke.**

What are the possible side effects of ELIQUIS?

- See **"What is the most important information I should know about ELIQUIS?"**
- ELIQUIS can cause a skin rash or severe allergic reaction. Call your doctor or get medical help right away if you have any of the following symptoms:
  - chest pain or tightness
  - swelling of your face or tongue
  - trouble breathing or wheezing
  - feeling dizzy or faint

Tell your doctor if you have any side effect that bothers you or that does not go away.

These are not all of the possible side effects of ELIQUIS. For more information, ask your doctor or pharmacist.

Call your doctor for medical advice about side effects. You may report side effects to FDA at 1-800-FDA-1088.

This is a brief summary of the most important information about ELIQUIS. For more information, talk with your doctor or pharmacist, call 1-855-ELIQUIS (1-855-354-7847), or go to www.ELIQUIS.com.

Manufactured by:
Bristol-Myers Squibb Company
Princeton, New Jersey 08543 USA
Marketed by:
Bristol-Myers Squibb Company
Princeton, New Jersey 08543 USA
and
Pfizer Inc
New York, New York 10017 USA

Based on 1289808A0 / 1289807A0 / 1298500A0 / 1295958A0
March 2014
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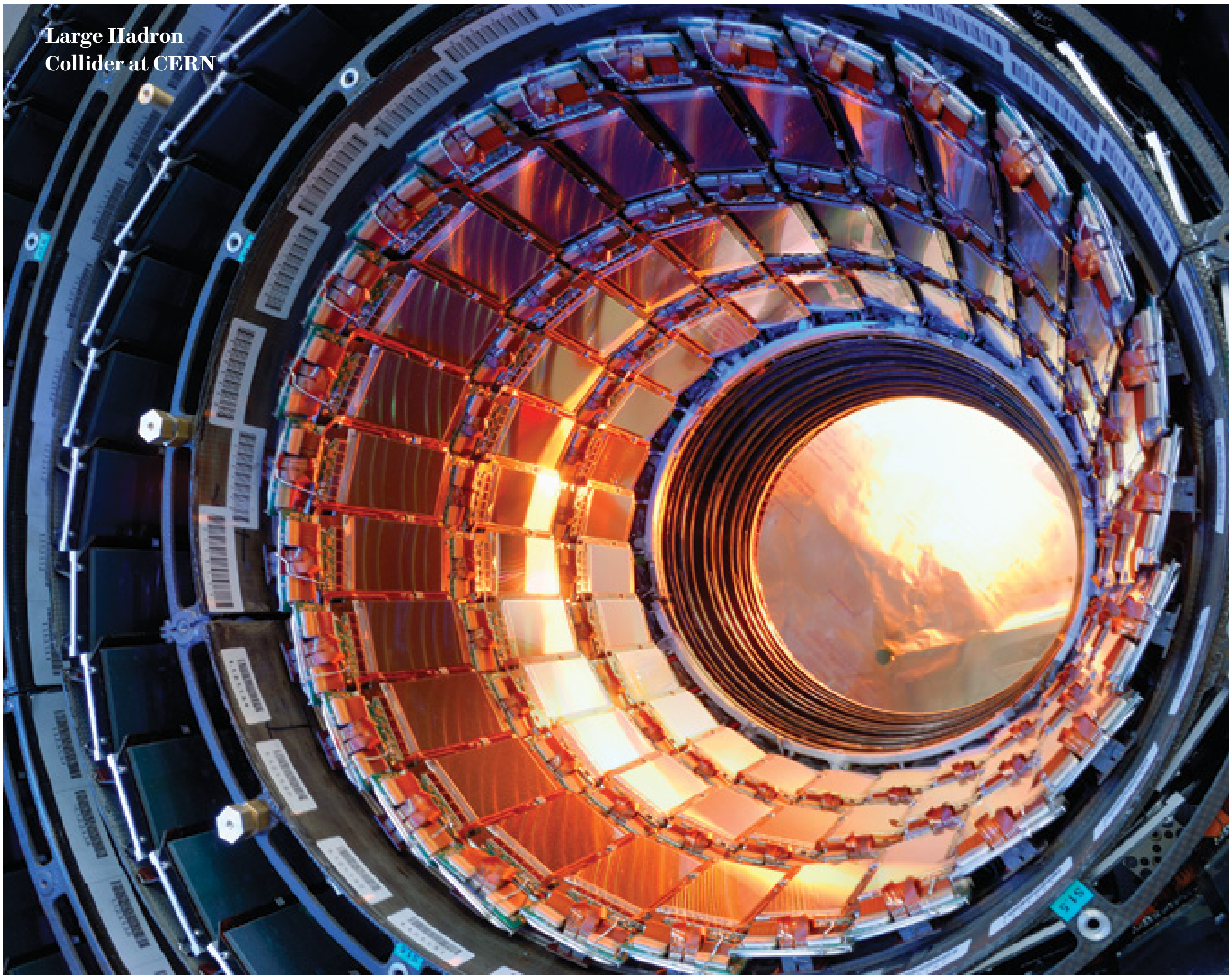


Large Hadron Collider at CERN

PHYSICS

Whispers of a Successor

The world's most powerful particle collider may have already spotted signs of supersymmetry

Physics is at an impasse. The path its practitioners have been following for decades, known as the Standard Model, came to a triumphant end in 2012, when researchers found the model's last undiscovered particle, the Higgs boson. The Standard Model describes the behavior of known particles remarkably well, but it cannot explain what dark matter is, among other things. Thus, many physicists have turned to supersymmetry, or SUSY.

SUSY posits that every known particle has a heavier partner, which gives it the power to explain dark matter. And some versions of it can account for why the Higgs boson, which gives other particles mass, has the mass that it does.

But the search for the exotic particles at the world's most powerful particle smasher, CERN's Large Hadron Collider (LHC) near Geneva, has so far come up empty, leading to no small amount of hand-wringing over SUSY's existence. "Lots of people are pessimistic," says David Curtin of Stony Brook University.

Two teams of researchers have lately been asking if perhaps physicists have simply missed SUSY trail markers. That could happen if supersymmetric particles do not reveal themselves dramatically but instead have just the right mass to decay into ordinary particles with unremarkable energies and other supersymmetric particles that can escape notice. In this way, SUSY particles could get lost in the shuffle of particles produced by more common Standard Model processes. "Signs of supersymmetry

COURTESY OF CERN

FURTHER READINGS AND CITATIONS ScientificAmerican.com/sep2014/advances

could be hiding right under our noses," says Curtin, a member of one team.

That indeed might explain the slight overabundance of two kinds of particles detected at the LHC in 2011 and 2012, before it shut down for an upgrade. In two separate preprint papers put forward in June, each team argues that the supersymmetric partner of the ordinary top quark, known as the stop, as well as two other superparticles, could explain the observations while also being in the right weight division to help account for the Higgs boson's mass.

But other researchers counter that an underestimate of Standard Model processes could account for at least some of the excesses. "It is too early to think that these measurements are likely pointers to new physics," says Dave Charlton, a member of one of the LHC teams that saw the excesses.

The issue may be resolved in 2015, when the souped-up proton smasher roars back to life. "We're all very eager to find evidence" for SUSY, says Ann Nelson, a theoretical physicist at the University of Washington, who was not involved in the new studies. "At this point, I'm cautious," she says but adds, "Huge signals start as little hints."

—Maggie McKee

CHEMISTRY

Salt Swap

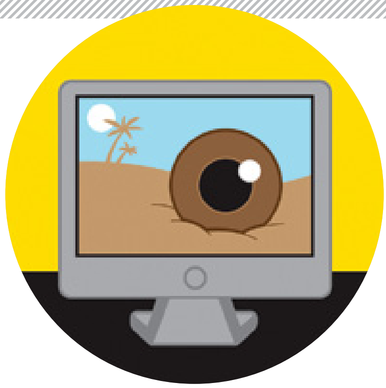
Changing a key ingredient of solar cells could make them safer and cheaper

Cadmium chloride is a nasty chemical. If it gets on the skin, it releases cadmium, which has been linked to cancer, lung disease and cardiovascular disease. And yet the expensive, dangerous compound has long been used as a coating for thin-film solar cells because it increases the efficiency of converting sunlight to energy. During manufacturing, chemists have to don protective gear and use fume hoods and other precautions to apply the coating, then carefully dispose of the dissolved cadmium waste.

Physicist Jon Major of the University of Liverpool in England and his team set out to find a replacement. They tested numerous alternative salts, including sodium chloride (table salt) and potassium chloride, and found that magnesium chloride yielded comparable efficiency. "We got cells as good as, if not better than, anything we ever got with cadmium chloride," Major says.

Magnesium chloride is also nontoxic, abundant and costs about 300 times less than cadmium chloride. It can even be applied with a cheap spray coater purchased on the Web. The team published its research online in June in *Nature*. (*Scientific American* is part of Nature Publishing Group.)

The new material applies to those solar cells that are made of cadmium telluride, the second most abundant type of solar cell in the worldwide market. Some experts are skeptical that the swap will yield big cost savings because the largest expense varies between manufacturers. Alessio Bosio, a physicist at the University of Parma in Italy, estimates savings will be "minimal," at about 15 percent. Still, physicist Julian Perrenoud of Switzerland's Empa, a materials science institute, who was not involved in the study, is optimistic. Using magnesium chloride, he says, "will reduce not only the health risks but also the production costs because the raw material is cheaper and much easier to dispose of." *—Joseph Bennington-Castro*



HEALTH

Dried Up

Too much screen time linked to changes in tears

Most Americans sit for at least six hours a day—an act that has been linked to obesity and heart disease, among other ailments. Mounting evidence suggests long hours staring at computer monitors may also be taking a toll on the eyes. People peering for hours into a screen tend to blink less often and have tears that evaporate more quickly, which dries out the eye and can cause blurred vision or pain. Left untreated, dry eye can lead to corneal ulcers and scarring.

Tears keep the eye moist and wash away dust or debris that could cause damage. But the tears of people with dry eye have less of a protein called mucin 5AC, which normally helps to keep tears sticky and spread evenly across the eye. A new study, based on 96 Japanese office workers, found that staring at a screen for eight hours or more is associated with lower mucin levels. The results were published online in June in *JAMA Ophthalmology*.

The good news is that the damage from staring at a screen is not likely to be permanent. Certain molecules that help to produce mucin remained roughly equal among test subjects with and without dry eye, regardless of their eyestrain status. Although larger studies need to be done, the findings confirm mucin as a possible target for future diagnosis and treatments of dry eye disease. Doctors already suggest taking regular breaks from the screen. Take a walk—or you may have a reason to tear up. *—Dina Fine Maron*

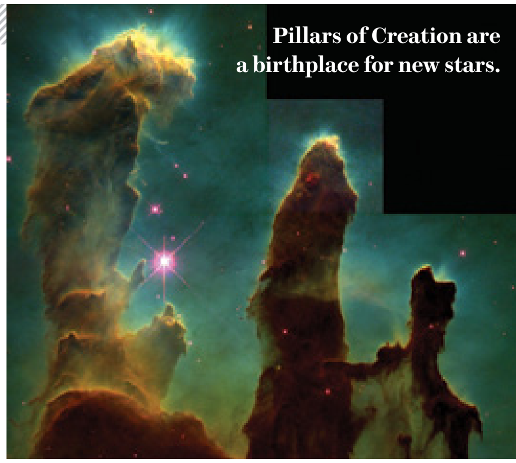
GETTY IMAGES

Illustrations by Thomas Fuchs

ASTRONOMY

An Origin Story

How the iconic Pillars of Creation arose could change the way astronomers think about O-stars



Pillars of Creation are a birthplace for new stars.

COURTESY OF NASA, ESA, STScI, AND J. HESTER AND P. SCOWEN *Arizona State University*

Remember the Pillars of Creation? Since the Hubble Space Telescope captured this spectacular photograph in 1995, it has appeared on posters, T-shirts and screen savers. Although everybody seems to be familiar with the pillars, the details of how they formed have been unclear. A computer simulation may have finally solved the mystery. Using the physics of gas flows, Cardiff University astronomer Scott Balfour and his colleagues have reproduced the famous pillar structures almost exactly.

The trio of gas columns, located inside the Milky Way's Eagle Nebula, earned its moniker because the columns are factories for creating stars. The pillars themselves are the product of a massive nearby O-type star that sculpted the gas with its powerful winds. O-stars are the universe's largest, hottest stars and live short lives that wreak havoc on their environments. Their intense radiation heats up surrounding gas to form expanding bubbles. And according to the new simulation, which spans 1.6 million years, columns with all the features of the Pillars of Creation naturally form along the outer rim of such bubbles as they expand and rip at the edges.

The simulation, which Balfour presented in June at the British Royal Astronomical Society's National Astronomy Meeting, also showed that O-stars have unexpected effects on star formation. Previous studies have suggested that O-stars initiate the creation of stars, which can often be found in their vicinity. The simulation, however, shows that the bubbles around O-stars often destroy star-forming clouds. In other cases, they compress surrounding gas to initiate the birth of stars sooner than they would have arisen otherwise, causing them to be smaller. "We were very surprised by that," Balfour says. Simulations by James Edward Dale, an astronomer at the University Observatory in Munich, also question whether O-stars really trigger star formation. Says Dale, "I find that the triggering is much less important than the destructive effects, which looks to be true in Balfour's simulations, too." It's a universal truth: destruction and creation go hand in hand.

—Clara Moskowitz

Bottom trawling in the Gulf of Mexico.

COURTESY OF NASA, IMAGE CREATED BY JESSE ALLEN, USING DATA OBTAINED FROM UNIVERSITY OF MARYLAND'S GLOBAL LAND COVER FACILITY

BIODIVERSITY

Hitting Rock Bottom

Deep-sea trawling harms biodiversity and disrupts carbon storage

Fishing boats have dragged nets across the seafloor in pursuit of bottom-feeding fish and crustaceans since the Middle Ages. In recent decades, motorized fishing fleets, powered by government subsidies, have taken heavier nets deeper and farther offshore. The annual haul from international waters in 2010 was reported to be worth more than $600 million.

To see how bottom trawling is changing the ocean's bottom, ecologist Antonio Pusceddu of the Marche Polytechnic University in Ancona, Italy, and his team took seafloor sediment samples at trawled and untouched sites off Spain's northeastern coast between 500 and 2,000 meters below the surface. They then counted the number of individuals and species in those samples and measured the amount of carbon in the sediment.

The final tally was grim. Trawling cut biodiversity by 50 percent and organic matter by 52 percent when compared with untouched sites. Meanwhile it slowed carbon cycling by 37 percent. Instead of settling on the seafloor, that stray carbon may acidify seawater or escape into the atmosphere. The team reported its results in June in the *Proceedings of the National Academy of Sciences USA.*

Despite images from early submersible expeditions of ghostly white dust settling onto a sandy floor, the deep sea is not a desert, Pusceddu says. Even parts of the sea that lack impressive corals or craggy seamounts can host important, if tiny, lifeforms. Some such creatures feed shrimp, the main target species for trawlers at Pusceddu's study site. Others consume carbon and trap it in the seafloor.

Bottom-feeding fish off the British Isles alone trap the equivalent of one million metric tons of carbon dioxide every year, according to a study published in June in the *Proceedings of the Royal Society B.* If kept intact, such biological processing could help countries offset carbon emissions, the authors write.

Better care is urgent: more powerful trawlers now reach deeper waters, oil drilling is moving ever downward, and Papua New Guinea just signed the first commercial sea-mining agreement. Plus, other work has found that the deepest-sea dwellers are among the longest-lived and slowest to recover from the effects of bottom trawling. The European Union may take the lead on this issue. Its newly elected parliament is reviewing draft legislation to limit the scope of deep-sea trawling. Chief scientist Elliott Norse of the Marine Conservation Institute in Seattle says the recent findings show decision makers that "they need to find ways to make fishing less harmful environmentally."

—Lucas Laursen

COMMENT AT ScientificAmerican.com/sep2014

BY THE NUMBERS

The world's first fully electric racing series, Formula E, kicks off in Beijing this month. After 10 hour-long races in cities worldwide, the International Automobile Federation (FIA) will announce the champion in June 2015. Here is a quick tour of the race car:

COURTESY OF FORMULA E OPERATIONS, LTD

PERFORMANCE

Acceleration:
0–62 mph in 3 s

Maximum Speed:
140 mph
(FIA limited)

POWER

Maximum Power:
(limited):
200 kW
(equivalent to 270 brake horsepower)

Race Mode:
133 kW
(equivalent to 180 bhp)

BATTERY

Weight:
441 lb

Voltage:
800 volts

Lasts:
25 min
(estimated)

Charging Time:
90 min
(estimated)

SOURCES: FIA FORMULA-E CHAMPIONSHIP *www.fiaformulae.com*; FORMULA E RACING *www.formulaeracing.com*

MEDICINE

Longer-Lasting Organs

Supercooled organ donations could last for days instead of hours

Today transplant organs remain viable for mere hours.

PATRICK ALLARD *Redux Pictures*

About 6,400 liver transplants took place in 2013 in the U.S., but demand far outpaces supply: more than 15,000 patients are on the current waiting list. Compounding the lack of availability, livers have only a small window of time to reach their destinations. The organs stay fresh for just 12 hours, during which they are kept on ice with a cold preservation solution. That is because freezing them is not an option—the process creates ice crystals that slice through the cells on thawing.

The waiting list for all organs has climbed above **122,000**

At Harvard Medical School, researchers are ditching the conventional storage technique in favor of a method that could extend the shelf life of livers and other organs. In results published in July in *Nature Medicine,* they report preserving viable rat livers for three whole days.

To preserve the organs for that long, the team used a specialized machine to erect a chemical buffer zone around the organ's cells. That buffer protected the cells' membranes against the threat of ice. The team then slowly cooled the livers to –6 degrees Celsius without actually freezing them—"supercooling" them.

In the experiment, six rats received livers supercooled for three days, and each one survived for three months (at which point the experiment ended, and they were euthanized). As expected, rats that received three-day-old livers preserved on ice all died. The supercooling method, however, cannot work indefinitely: only about 60 percent of rats receiving livers stored for four days managed to survive for the study's duration. Next, the team plans on testing the method with pigs and humans.

The success with this approach, the authors say, could extend the reach of organ transplants and so provide greater access to patients. In the U.S., the national map for liver distribution is currently far from equal. For instance, patients living near trouble spots, such as big highways prone to traffic accidents, have a higher chance of receiving a viable liver.

In the future, supercooling may also support research with organs on a chip, according to Korkut Uygun, who was part of the liver experiment and is an assistant professor of surgery at Harvard Medical School. Organs on a chip are collections of laboratory-grown human cells designed to mimic the organs in the body. They are a highly anticipated way to study how our organs work and how they respond to various drugs. Supercooling would make shipping them from manufacturing labs to researchers more practical. For now the promise of getting transplant organs to patients remains the primary focus. The waiting list for all organs has climbed above 122,000. *—Dina Fine Maron*

COMMENT AT ScientificAmerican.com/sep2014

Arctic ice harbors bits of nylon and polyethylene.

GORDON WILTSIE *Getty Images*

ENVIRONMENT

Plastic on Ice

Trillions of brightly colored bits are in the Arctic deep freeze

An untold amount of plastic pollution finds its way into the ocean every year. No one knows for sure what becomes of all that garbage. Much of it most likely erodes into microplastic, tiny flecks smaller than five millimeters in diameter, which can take up pollutants and are often ingested by marine animals, including fish and crustaceans.

Unexpectedly, trillions of those particles end up in Arctic sea ice, according to a paper published in May in the scientific journal *Earth's Future.* The study found that sea ice contains up to 240 microplastic particles per cubic meter—as much as 2,000 times the density of the particles that are estimated to float in the Great Pacific Garbage Patch. "We know that microplastic is found in oceans worldwide, but it is surprising that it's found in such an abundance in Arctic sea ice," says Rachel Obbard, a materials scientist and engineer at Dartmouth College and lead researcher of the study. When ice forms at the surface of the ocean, it traps anything that happens to be floating there. The freezing process, she says, seems to be concentrating the trapped particles, which otherwise would eventually sink to the seafloor.

Obbard did not set out to examine sea ice for plastic. Instead she and a student were looking for algae in four ice cores collected from remote locations in the Arctic Ocean. When she melted and filtered the samples, however, she found blue, red, green and black bits. "These brightly colored things," she says, "just jumped right out at me."

Extrapolating from the samples, Obbard and her colleagues estimate that up to seven trillion pieces of microplastic in total could be released as Arctic sea ice melts because of climate change. Some researchers say summer in the Arctic may be ice-free around 2100. Others project it could happen within the next decade.

—Rachel Nuwer

WHAT IS IT?

Kevlar can fend off bullets traveling at hundreds of meters per second no problem, but the supertough synthetic fiber is no match for debris hurtling through outer space at several kilometers per second. In June, engineers at the Fraunhofer Institute for High-Speed Dynamics in Germany ran a space-debris simulation to test the fiber. Small meteoroids and other space flotsam can hit resupply vessels to the International Space Station, so the vessels have shields. Those shields are made up of an aluminum wall covering a layer of Kevlar and Nextel, a ceramic fiber. In the simulated impact, the engineers fired a 7.5-millimeter-diameter aluminum bullet from a specialized gun at a model shield. Traveling at about seven kilometers per second, the bullet punched a fist-sized hole through the Kevlar-Nextel fabric. Despite the damage, this shield did its job: dissipating the energy of the bullet and so protecting the inner walls. *—Annie Sneed*

COURTESY OF ESA

EDUCATION

Sleeping through High School

The later classes start, the more academic performance improves

Parents, students and teachers often argue, with little evidence, about whether U.S. high schools begin too early in the morning. In the past three years, however, scientific studies have piled up, and they all lead to the same conclusion: a later start time improves learning. And the later the start, the better.

Biological research shows that circadian rhythms shift during the teen years, pushing boys and girls to stay up later at night and sleep later into the morning. The phase shift, driven by a change in melatonin in the brain, begins around age 13, gets stronger by ages 15 and 16, and peaks at ages 17, 18 or 19.

Does that affect learning? It does, according to Kyla Wahlstrom, director of the Center for Applied Research and Educational Improvement at the University of Minnesota. She published a large study in February that tracked more than 9,000 students in eight public high schools in Minnesota, Colorado and Wyoming. After one semester, when school began at 8:35 A.M. or later, grades earned in math, English, science and social studies typically rose a quarter step—for example, up halfway from B to B+.

Two journal articles that Wahlstrom has reviewed but have not yet been published reach similar conclusions. So did a controlled experiment completed by the U.S. Air Force Academy, which required different sets of cadets to begin at different times during their freshman year. A 2012 study of North Carolina school districts that varied school times because of transportation problems showed that later start times correlated with higher scores in math and reading. Still other studies indicate that delaying start times raises attendance, lowers depression rates and reduces car crashes among teens, all because they are getting more of the extra sleep they need.

And the later the delay, the greater the payoff. In various studies, school districts that shifted from 7:30 to 8:00 A.M. saw more benefits than those that shifted from 7:15 to 7:45 A.M. Studies in Brazil, Italy and Israel showed similar improvements in grades. The key is allowing teens to get at least eight hours of sleep, preferably nine. In Europe, it is rare for high school to start before 9:00 A.M.

Studies also show that common arguments against later start times ring hollow. In hundreds of districts that have made the change, students do not have a harder time fitting in after-school activities such as sports or in keeping part-time jobs. "Once these school districts change, they don't want to go back," Wahlstrom says.

Even "the bus issue" can work out for everyone. Many districts bus kids to high school first, then rerun the routes for the elementary schools. Flipping the order would bring high schoolers to class later and benefit their little sisters and brothers; other studies show that young children are more awake and more ready to learn earlier in the morning. —*Mark Fischetti*

Select Schools Starting Later Hours This Month

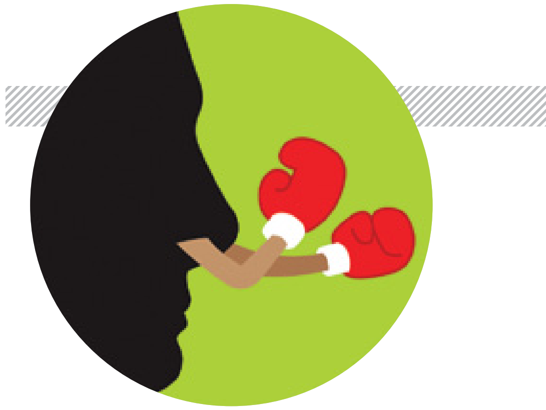
North Olmsted High School
Ohio, 8:00 A.M.
40 minutes later

Wabash High School
Indiana, 8:35 A.M.
50 minutes later

Little Elm High School
Texas, 9 A.M.
25 minutes later

Buford Middle School
Virginia, 8:30 A.M.
50 minutes later

Elmira High School
New York, 8:50 A.M.
65 minutes later



BIOLOGY

Pick a Fight

Taste receptors in the nose battle bacterial invaders

Our noses are loaded with bitter taste receptors, but they're not helping us taste or smell lunch. Ever since researchers at the University of Iowa came to this conclusion in 2009, scientists have been looking for an explanation for why the receptors are there. One speculation is that they warn us of noxious substances. But they may play another role too: helping to fight infections.

In addition to common bitter compounds, the nose's bitter receptors also react to chemicals that bacteria use to communicate. That got Noam Cohen, a University of Pennsylvania otolaryngologist, wondering whether the receptors detect pathogens that cause sinus infections. In a 2012 study, his team found that bacterial chemicals elicited two bacteria-fighting responses in cells from the nose and upper airways: movement of the cells' projections that divert noxious things out of the body and release of nitric oxide, which kills bacteria.

The findings may have clinical applications. When Cohen recently analyzed bitter taste receptor genes from his patients with chronic sinus infections, he noticed that practically none were supertasters, even though supertasters make up an estimated 25 percent of the population. Supertasters are extra sensitive to bitter compounds in foods. People are either supertasters or nontasters, or somewhere in between, reflecting the genes they carry for a receptor known as T2R38.

Cohen thinks supertasters react vigorously to bacterial bitter compounds in the nose and are thus resistant to sinus infections. In nontasters the reaction is weaker, bacteria thrive and sinus infections ensue. These results suggest that a simple taste test could be used to predict who is at risk for recurrent infections and might need more aggressive medical treatment. *—Jill U. Adams*

CONSERVATION

Bat Deterrents

How to keep bats away from wind turbines

Wind turbines are a notorious hazard for birds, but less well known is the danger they pose to bats. In 2012 turbines killed more bats than birds, and the numbers of the dead were substantial: about 888,000 bats were found on wind farms, compared with 573,000 birds.

Migrating bats such as the hoary bat, which can travel from as far as northern Canada to Argentina and Chile, make up most of those fatalities because they often navigate through areas dotted with wind farms. Yet researchers have also found carcasses of cave-hibernating bats, including the little brown bat and the northern long-eared myotis—two species that have been devastated by the fungal disease white nose syndrome and that are now being considered for protection under the Endangered Species Act.

Because of white nose syndrome, mounting public pressure and scrutiny from wildlife officials have become a major motivator for wind energy companies to figure out how to prevent bat deaths. Three targeted strategies are in the works. *—Roger Drouin*

JOEL SARTORE *Getty Images*

OPERATIONAL CHANGES

Turning turbines off from summer to late fall during low-wind conditions—when bats are most active—is the single most promising option to protect them, according to Ed Arnett, a pioneer of bat and wind energy research efforts. In tests at the Casselman Wind Power Project in Pennsylvania, small changes to turbine operations reduced bat mortality significantly. During nights from July to October in 2008 and 2009, operators shut down the turbines when wind speeds were below 6.5 meters per second. As a result, bat deaths were reduced by 44 to 93 percent, with less than 1 percent annual power loss.

BOOM BOXES

Ultrasonic "boom boxes" that emit continuous high-frequency sounds from 20 to 100 kilohertz deter bats from getting too close to turbines by interfering with their echolocation. "We find fewer dead bats at these treatment turbines," says Cris Hein of Bat Conservation International (BCI). During tests the organization performed in 2009, turbines with the deterrence device killed 21 to 51 percent fewer bats. General Electric Power & Water recently partnered with BCI to develop boom boxes for commercial availability. And new research shows that most of the winged mammals approach turbines from the leeward side, which could provide insight into optimal placement.

ULTRAVIOLET LIGHT

UV light is not discernible to humans, but many bat species are sensitive to it, so several researchers and companies are studying how to use the light to keep bats away from turbines. The National Science Foundation recently awarded a $150,000 grant to Lite Enterprises, based in Nashua, N.H., to test the technical and commercial viability of this technology. "What's promising is that it would extend further than the ultrasonic deterrence and could be cheaper to install," Hein says. The ultrasonic deterrence's effective range is about 20 to 40 meters from the source, whereas the UV-light-emitting device could extend 50 meters or more.

JOEL SARTORE *Getty Images*

COGNITION

The Thinker

Evidence suggests that humans are not the only animals capable of introspection

When you do not know the answer to a question, say, a crossword puzzle hint, you realize your shortcomings and devise a strategy for finding the missing information. The ability to identify the state of your knowledge—thinking about thinking—is known as metacognition. It is hard to tell whether other animals are also capable of metacognition because we cannot ask them; studies of primates and birds have not yet been able to rule out simpler explanations for this complex process.

Scientists know, however, that some animals, such as western scrub jays, can plan for the future. Western scrub jays, corvids native to western North America, are a favorite of cognitive scientists because they are not "stuck in time"—that is, they are able to remember past events and are known to cache their food in anticipation of hunger, according to psychologist Arii Watanabe of the University of Cambridge. But the question remained: Are they *aware* that they are planning?

Watanabe devised a way to test them. He let five birds watch two researchers hide food, in this case a wax worm. The first researcher could hide the food in any of four cups lined up in front of him. The second had three covered cups, so he could place the food only in the open one. The trick was that the researchers hid their food at the same time, forcing the birds to choose which one to watch.

If the jays were capable of metacognition, Watanabe surmised, the birds should realize that they could easily find the second researcher's food. The wax worm had to be in the singular open cup. They should instead prefer keeping their eyes on the setup with four open cups because witnessing where that food went would prove more useful in the future. And that is exactly what happened: the jays spent more time watching the first researcher. The results appeared in the July issue of the journal *Animal Cognition.*

Friederike Hillemann, who studies corvids at the University of Göttingen in Germany, thinks the experiment is an elegant way to determine whether animals are capable of reasoning about their own knowledge states. Although this experiment did not directly test consciousness, the findings are exciting because they provide further evidence that humans are not the only species with the ability to think about their thought processes. Or, as Watanabe put it, "some birds study for a test like humans do." *—Jason G. Goldman*

KNOW THE JARGON

Induced seismicity:
(*n.*) Earthquakes caused by human activities.

Not long ago earthquakes in Oklahoma were rare. Not anymore. Twenty earthquakes of 3.0 magnitude or greater shook Oklahoma in 2009. The state has seen a 40-fold increase in seismicity since 2008. The cause? Humans, according to new research in *Science*. The study confirmed what geologists have been speculating for years: that underground water disposal by oil and gas companies causes earthquakes.

Millions of gallons of wastewater are produced every month in Oklahoma as a result of extracting oil and natural gas from the ground. The companies inject this wastewater into wells to dispose of it, which raises the groundwater pressure and can stress geologic faults. "Normally, earthquakes occur naturally because of plate motions," says Katie Keranen, a geophysics professor at Cornell University and the study's lead author. "But if you inject enough water into the earth, you can influence the cycle of earthquakes."

After using hydrogeologic models with the seismic data, Keranen and her colleagues concluded that four disposal wells southeast of Oklahoma City likely caused the Jones swarm, a group of earthquakes that accounted for 20 percent of seismicity in the central and eastern U.S. between 2008 and 2013. The team also found that wastewater injection induced earthquakes as far as 30 kilometers away from the wells, much farther than previously thought.

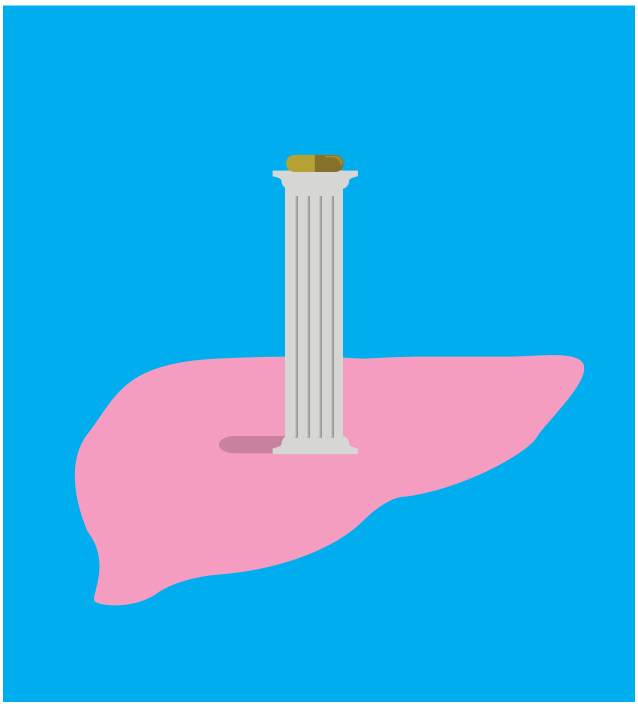
Geologists have used the term "induced seismicity" to describe earthquakes triggered by mining, dams, underground nuclear tests and wastewater injection. As oil and gas extraction methods become more common and more studies connect their disposal methods to seismic activity, the term will be one to watch. *—Annie Sneed*

COMMENT AT ScientificAmerican.com/sep2014

Jessica Wapner is a freelance writer and author of *The Philadelphia Chromosome: A Genetic Mystery, a Lethal Cancer, and the Improbable Invention of a Life-Saving Treatment,* which has recently been reissued.

The Solid-Gold Wonder Drug

A long, difficult and costly research effort gives doctors a new cure for hepatitis C



A decades-long search for better treatments for a debilitating liver disorder is finally coming to fruition. Later this year the U.S. Food and Drug Administration is expected to approve a new pill that can cure hepatitis C—a chronic infection that afflicts about 170 million people worldwide and annually kills 350,000 people, including 15,000 in the U.S.—faster and with fewer side effects than current remedies.

The breakthrough treatment comes, however, at a price that may place it out of reach for all but the wealthiest or best-insured patients. It will contain two drugs, one of which is already available at $1,000 per dose, or $84,000 for a complete 12-week course. The dual-drug combination will likely cost even more, which has prompted outrage from physicians and patient advocates alike, as well as plans from insurers to ration the combination when it becomes commercially available.

Over the coming months, physicians, patients, economists and insurance companies will no doubt hotly debate whether the treatment is worth the full asking price. There is little doubt, however, that the medication's effectiveness is unprecedented and that its development is a significant achievement. A closer look at the complex chemical problems that needed to be solved to develop the cure shows why.

FAST AND INVISIBLE

CURES SOMETIMES RESULT from happy accidents—think penicillin mold growing in an overlooked petri dish. More often they require years of research into what is causing the problem in the first place. Understanding the science behind the new hepatitis C treatment starts with deciphering the meaning of the virus's name.

"Hepatitis" is a general term that refers to severe swelling or inflammation of the liver in response to certain drugs, toxins, excessive alcohol or infections—whether from bacteria or viruses. The letter C refers to the third in a series of viruses that researchers have isolated that specifically target and damage the liver. By the mid-1970s investigators had developed blood tests to identify hepatitis A, which typically spreads when infected individuals improperly handle food or water, and hepatitis B, which is often transmitted during sexual intercourse, the sharing of needles or contact with contaminated blood.

Soon after, researchers realized that a third form of viral hepatitis was silently spreading around the globe and that it was more likely than hepatitis A or B to result in permanent liver damage. By 1989 they had identified the virus that caused the condition. They also determined that the virus's genes mutate very fast—a process that has generated several equally successful varieties, called genotypes, and rendered an effective vaccine impossible to create so far. Hepatitis B virus, in contrast, does not evolve as quickly, and a vaccine against it has been available since the 1980s. Infection with hepatitis A virus, which usually causes symptoms within days, can also be prevented with a vaccine.

Standard treatment for hepatitis C has long been a synthetic, injectable version of interferon, one of the immune system's most powerful proteins, plus the antiviral drug ribavirin. The combination helps 25 to 75 percent of patients, depending on the genotype of the virus. But the side effects, including severe flulike symptoms, fatigue, depression and anemia, are often intolerable. In addition, the virus often becomes resistant to medication, allowing the disease to worsen.

TOWARD A CURE

DEVELOPING EFFECTIVE TREATMENTS against the virus required researchers to understand the structure of the various proteins that formed its outer shell, as well as the precise sequence of its genetic material, which is made up of RNA—a process that took the better part of the 1990s and involved researchers working around the globe in government, academia and industry.

With this information in hand, scientists still faced a long and costly phase of trial and error. They chose what looked like

Illustration by Oliver Munday

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a promising target for treatment: an enzyme known as a protease that the virus depends on to make copies of itself. After several false starts, researchers at Vertex Pharmaceuticals, in collaboration with others, developed a protease inhibitor known as telaprevir, while scientists at Schering-Plough (which merged with Merck in 2009), created one called boceprevir. In clinical trials, 60 to 75 percent of patients receiving the standard treatment—ribavirin and interferon—as well as the two new drugs had no detectable signs of the virus in their bloodstream, compared with 44 percent or fewer patients receiving the typical treatment alone.

The FDA approved the new drugs in 2011, but the sense of triumph felt by many in the medical community soon gave way to disappointment. The medications had harsh side effects and worked only for those patients with a particular genetic variant of the virus known as genotype 1, which is the most common type in the U.S. and Canada but rare in many other countries with hepatitis C epidemics. Moreover, the continued need for interferon and ribavirin, with their attendant side effects, was a huge drawback.

As enthusiasm for telaprevir and boceprevir waned, other viral proteins emerged as promising drug targets. What scientists had learned from their earlier research, however, was that inactivating an enzyme or protein was not enough. To stop hepatitis C, any effective drug also had to incorporate itself into the virus's genetic code, where it would need to halt the virus's ability to make new copies of its genes and thus to make new virus. In addition, to avoid potentially debilitating side effects, the medication had to get to the liver quickly and directly, bypassing as many other organs as possible.

A company called Pharmasset had been looking at a group of drugs known as nucleotide analogues, which met some of these criteria, since the mid-2000s. Constructed by stitching molecules that resemble the building blocks of DNA and RNA with a molecule made of phosphorus plus oxygen (known as a phosphate), these compounds inserted themselves into the virus's genes, where they promptly fell apart, interfering with viral replication.

Researchers then ran into a few big biochemical problems. Because the nucleotide analogues were water-soluble, they could not traverse the fatty lining of the intestine (fats and water do not mix) to reach the bloodstream and then the liver. In addition, the phosphate group carried a double negative electrical charge, further restricting its ability to move across the intestine's electrically neutral membrane. Finally, other enzymes in the liver easily dislodged the phosphate group from the nucleotide analogue, rendering the compound ineffective.

Michael Sofia, then at Pharmasset, solved the problems by adding two compounds known as esters to the analogue. This addition both shielded the negative charges and made the drug greasy, enabling it to leave the gut. Once inside liver cells, the enzymes that had initially interfered with the phosphate group hit the ester molecules instead, leaving the active drug free to do its job. The new formulation was named sofosbuvir in Sofia's honor; the company was purchased, in 2011, by Gilead for $11 billion.

In a large study, 295 out of 327 patients treated with sofosbuvir, as well as ribavirin and interferon, showed no signs of the virus in their blood after 12 weeks. In a more advanced trial, 12 weeks of sofosbuvir plus ribavirin yielded the same results as 24 weeks of interferon plus ribavirin: 67 percent of patients had no evidence of the virus in their blood (although side effects such as fever and depression were fewer among patients who did not receive interferon). The FDA approved sofosbuvir in late 2013 as a treatment for hepatitis C in combination with ribavirin.

Still, investigators pushed to make further improvements. During sofosbuvir's development, they had studied other drugs that inhibited different viral proteins and that might eliminate the need for continued use of interferon and ribavirin. So they ran another study of sofosbuvir plus one such complementary drug, daclatasvir, made by Bristol-Myers Squibb. The result: nearly all patients were cured of the disease, with far fewer side effects than before. Since then, Gilead has run three additional studies of sofosbuvir paired with a different drug, ledipasvir. The combination cured at least 94 percent of patients with genotype 1 disease.

It is this combination, mixed in a single daily pill, that industry watchers expect the FDA to approve by October 2014. It heralds a new era of curative treatment for patients with hepatitis C. Similar drugs that work equally well for all genotypes are now in the final stages of clinical development.

FINANCIAL RESISTANCE

BECAUSE THE SOON TO BE RELEASED combination pill cures hepatitis in just 12 weeks—eliminating the need for and the expense of treating an otherwise chronic illness—it may end up costing less overall than previous treatments. (Gilead is not expected to announce the retail price of the pill until it receives FDA approval.) Of course, that does not mean that patients will be to afford it.

David Thomas, director of the division of infectious diseases at Johns Hopkins University, considers the price an impediment to health care around the globe, despite the potential savings. Many people in the U.S. with hepatitis C are poor, and several hundred thousand are incarcerated. "Medication that costs more than $100,000 won't make a big impact in prisons in Russia or for drug users in Pakistan," Thomas says. Within the U.S., copayments may put the treatment out of reach.

The price tag has also struck a nerve among insurers and other third-party payers. "We've never had such a high-cost drug for such a large population," says Brian Henry, a spokesperson at Express Scripts, which manages benefits for more than 3,500 companies. "Treatment for one hepatitis C patient now can take up a huge portion of a small business's budget for drug spending."

The manufacturer insists that cost will not prevent access. As it has for its HIV drugs, Gilead plans to provide patient assistance within the U.S., to license the drug (for a fee) to select generic manufacturers outside the U.S., and to lower prices in low- and middle-income countries. In Egypt, which has the world's highest rate of hepatitis C, sofosbuvir costs $300 for a 28-day supply.

At the FDA meeting to review sofosbuvir for approval, Sofia listened to testimony from a patient who had been cured by the new drugs at practically the last minute. "Stories like this," Sofia says, "put everything one does in perspective." How many other patients get to tell such stories remains to be seen. SA

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David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Unsettled Score

Will digital orchestras replace live musicians in concert?

This August's production of Richard Wagner's four-opera *Ring* cycle in Hartford, Conn., has been postponed.

Rather than hiring pit musicians, producer Charles M. Goldstein had intended to accompany the singers with sampled instrument sounds, played by a computer. Not a CD, not a synthesizer; the computer triggers the playback of individual notes ("samples") originally recorded from real instruments.

The reaction of professional musicians—and, of course, the musicians' union—was swift and furious. New York City's Local 802 president called it operatic karaoke. Hate mail poured in. In the end, the opera's music director, as well as two of the stars, withdrew from the production.

I know exactly what Goldstein must be feeling right about now. For my first 10 years out of college, I worked on Broadway shows as a musical director and arranger. In 1993 the group now called the Broadway League (of theater owners) contacted me. They wanted me to demonstrate how well computers and samplers could serve a live performance.

I was flattered that powerful producers were seeking the advice of little 30-year-old me. I was all set to help out—until I started getting anonymous threats on my answering machine.

It turns out, the Broadway League and Local 802 were at the bargaining table, and the league wanted to use technology as leverage. The unspoken message: "If we can't reach an agreement, our shows will go on—without live music."

I bowed out. I was a Local 802 member *and* employed by a Broadway producer; I was in no position to choose a side. Even today, though, I'm deeply empathetic to both parties.

Musicians and music lovers argue that live orchestras are essential. Nobody buys a ticket to listen to a CD; there's something thrilling about musicians working as a unified artistic element. Of course, the musicians' unions also have a less noble interest: keeping their dwindling ranks employed.

For their part, producers often argue that there might be no show at all without a digital orchestra; live musical theater is expensive. Just look at the list of U.S. opera companies that have closed in the past few years: Opera Cleveland, Opera Pacific, San Antonio Opera and, shockingly, New York City Opera.

Do we really want to eliminate opera altogether or watch it with a piano accompaniment—a live player, yes, but a puny sound? Those outcomes serve nobody, including the public.

As technology has marched on, the musicians have lost two additional arguments: that fake music doesn't sound as good as real players and that audiences demand live players.

These days you can't tell a live but amplified orchestra from a high-end sampled one. And—tragically, to me—it doesn't seem as though, in the end, showgoers care much. During a 1993 musicians' strike, management at the John F. Kennedy Center for the Performing Arts in Washington, D.C., announced that its production of *The Phantom of the Opera* would use taped accompaniment. About 90 percent of ticket holders attended anyway.

It's likely Goldstein is correct that a full live orchestra would make his *Ring* cycle too expensive to produce. But if we let him proceed, what's to stop producers from running with that argument, eventually replacing all live players to save money? It's a fraught situation, rife with potential for abuse on both sides.

History is not on live music's side. Canned music has largely replaced live players at dance performances, restaurants, school plays and community theaters. Nobody seems to bat an eye.

Further, the efficiencies and economies of digital technology have destroyed the old models in other creative industries: book publishing, moviemaking, pop music recording, and so on.

The battle between technology and live music will rage on for years, with passion on both sides. But as a musician and a live music fan, it's painful for me to say it: the long-term future of live pit musicians doesn't look especially upbeat. SA

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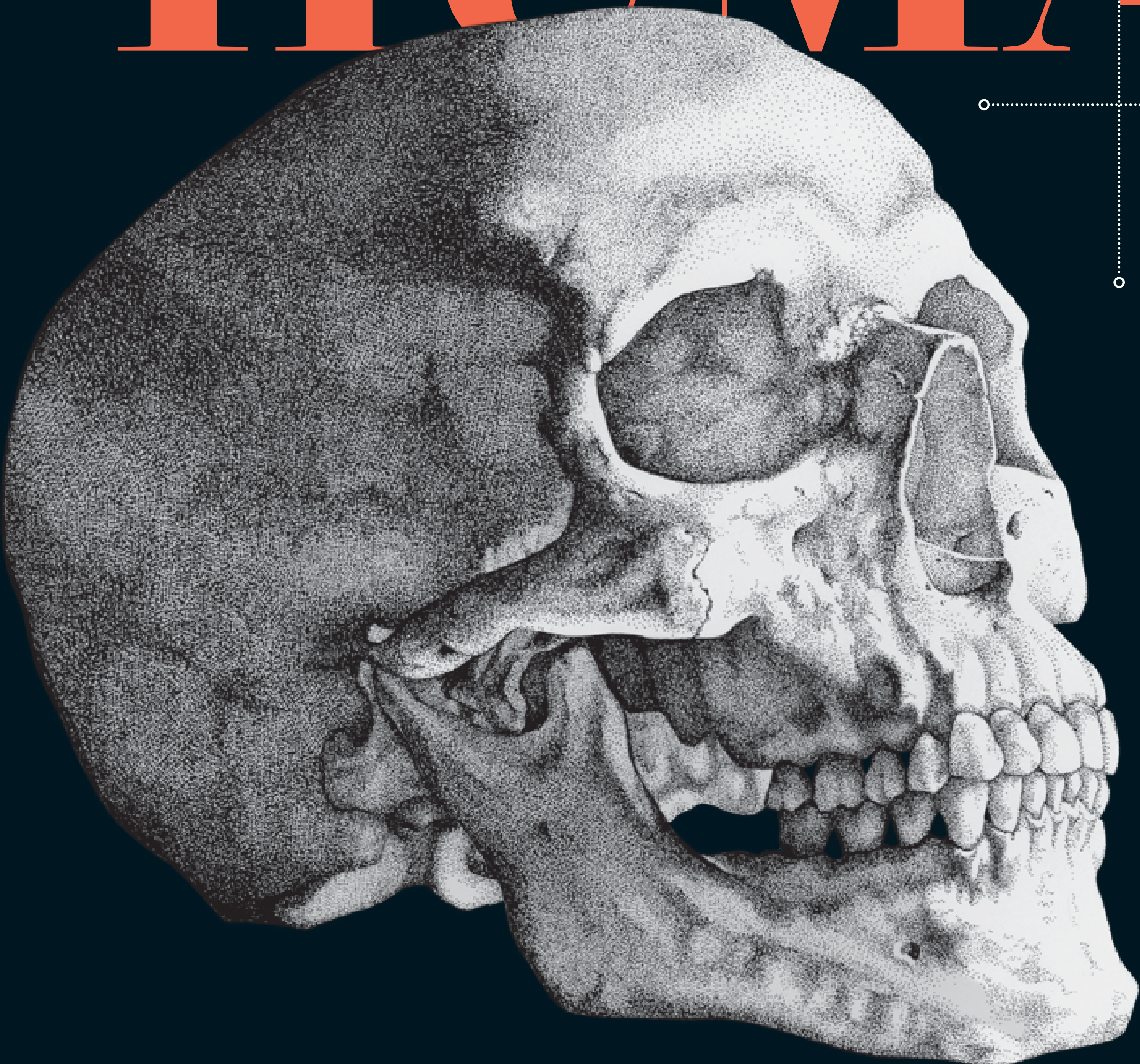
Inside the battle to keep music live: ScientificAmerican.com/sep2014/pogue

Illustration by Edel Rodriguez

THE HUMA



N SAGA

EVOLUTION REWRITTEN

Awash in fresh insights, scientists have had to revise virtually every chapter of the human story

By Kate Wong

THROUGH THE POST BOX, UP THE DRAGON'S BACK, DOWN THE CHUTE AND OVER TO THE PUZZLE Box. Last fall the world followed, via tweets, blogs and videos, as scientists negotiated these fancifully named landmarks of the underground system of caves known as Rising Star just outside Johannesburg, South Africa. The tight squeezes and steep drops made for difficult, dangerous work. The researchers, however, had their eyes on the prize: fossilized remains of an extinct member of the human family. Paleoanthropological fieldwork is usually done in secret, but this time the scientists posted thrilling multimedia missives along the way for all to see.

Cavers had spotted the bones in September while surveying the lesser-known caves of the famed Cradle of Humankind region. Researchers were certain the bones were important even without knowing their age and species: most of the individuals represented in the human fossil record consist of either skull fragments or bones from the neck down. This discovery had both. The association of skull and skeletal remains alone would have earned the find a prominent spot in any human origins textbook. After excavators began unearthing the bones, they realized that they had something even bigger on their hands. It was not just one individual's remains on the cave floor, as they originally thought, it was many—an entire population of early humans.

In two short expeditions spanning a total of four weeks, a team working under the direction of paleoanthropologist Lee Berger of the University of the Witwatersrand, Johannesburg, hauled more than 1,500 bones and bone fragments from their resting spot 30 meters underground up to the expedition's science tent, where

Illustration by Katy Wiedemann

SPELUNKING SCIENTISTS, including K. Lindsay Eaves (*above left*), have recovered more than 1,500 fossils of early members of the human family (*above right*) from the Rising Star cave system outside Johannesburg, South Africa. The researchers made 3-D scans of the fossil chamber to document their work as they excavated (*right*).

COURTESY OF ELEN FEUERRIEGEL (*Eaves*); COURTESY OF JOHN HAWKS (*teams with fossils and at computer screen*)

researchers catalogued the fossils and filled safe after safe with the ancestral remains. Incredibly, they only scratched the surface: a myriad of bones await in the chamber. At this rate, Rising Star is shaping up to be one of the richest human fossil sites on record.

The exact significance of the find is not yet clear. Although the team went public with the recovery efforts, it has kept the scientific details under wraps. Maybe the bones represent a species new to science, one that, like the fossils Berger and his colleagues found at the nearby site of Malapa just a few years ago, casts light on the shadowy origins of our genus, *Homo.* Perhaps a pattern will emerge from the large number of individuals at the site that will reveal the structure of their social groups. Possibly, comparison of the human remains with any remains of animals at the site will illuminate how they ended up in the cave in the first place. Answers are in the offing: the discovery team is now preparing its formal description and analysis of the bones for publication.

We observers may not yet know how these fossils will rewrite the story of our origins, but history tells us that they will indeed rewrite it. The Rising Star find is only the latest in a rash of discoveries since the start of the new millennium that are upending bedrock tenets of human evolution. New fossils are adding branches to our family tree; climate data are revealing the conditions under which our predecessors evolved their hallmark traits; primate studies are homing in on exactly what distinguishes us cognitively from our great ape cousins; DNA analyses are illuminating how ancient populations interacted—and how our species continues to change. Awash in this flood of fresh insights, scientists have had to revise virtually every chapter of the human saga, from the dawn of humankind to the triumph of *Homo sapiens* over the Neandertals and other archaic species. Never has the science of human origins felt more vital; never has our story been such a compelling read.

To appreciate just how far paleoanthropology has advanced in recent years, let us revisit the late 1990s, a time when scientists seemed to have a pretty good handle on our evolution. The fossil record of humans was relatively rich (particularly compared with the then nonexistent records of our closest living relatives, the African great apes), and genetic evidence, where applicable, seemed to fit the fossil tale. Back then the conventional wisdom, in short, was that the very first hominins (the group that includes modern humans and their extinct relatives) emerged in East Africa sometime before 4.4 million years ago, followed by our genus, *Homo,* a bit more than two million years ago. Hominins did not make it off the continent until little more than a million years ago, after which they began to fil-

SCIENTIFIC AMERICAN ONLINE Read more about recent paleoanthropological discoveries at ScientificAmerican.com/sep2014/wong

ter into other regions of the Old World. As they settled in these new locales, new *Homo* species arose, including the Neandertals in Eurasia. These species thrived for hundreds of thousands of years until a new species from Africa began to spread across the globe. Cleverer by half and armed with cutting-edge technology and the gift of gab, *H. sapiens* took the world by storm, driving the Neandertals and other archaic forms to extinction as it rose to prominence. There was no mingling, no hybrid love children to carry Neandertal genes into the next generation, just a straight-up replacement of the old guard by the new in which *H. sapiens* at best outcompeted and at worst killed off the hominins it encountered as it expanded out of Africa. By 30,000 years ago or thereabouts, ours was the last hominin species standing. Or so the story went.

As it turns out, fossil and genetic evidence amassed since then has cast doubt on or downright disproved every element of that CliffsNotes accounting of our origins. For example, seven-million-year-old fossils from northern Chad's Djurab Desert have extended the human fossil record by more than two million years and raised the possibility that hominins emerged not in East Africa but to the west. And the nearly two-million-year-old fossils from Malapa in South Africa hint that *Homo* itself may have gotten its start in that part of the continent rather than East Africa.

Fossils from Dmanisi in the Republic of Georgia, dated to 1.78 million years ago, show that hominins began pushing out of Africa hundreds of thousands of years earlier than originally envisioned, long before *Homo* had evolved the long legs, enlarged brain and sophisticated tool kit that had previously been thought to power this expansion. And the stunning discovery of a tiny hominin species that lived on the island of Flores in Indonesia until around 17,000 years ago raises the possibility that our forebears started spreading out of Africa even earlier than the Dmanisi fossils would suggest: the exceptionally small body and brain of *Homo floresiensis,* as the Indonesian remains are known, might be traits from an australopithecinelike ancestor that blazed a trail out of Africa two million years ago or more.

Arguably, no chapter of the human odyssey has been so dramatically rewritten as the one detailing the ascent of *H. sapiens*. Far from being an evolutionary slam dunk, destined for world domination from the outset, the fossil record now paints a picture of a species that had no sooner debuted than it nearly went extinct as a result of climate change. Neither is the cognitive divide between *H. sapiens* and archaic species nearly so pronounced as some scholars had envisioned. Discoveries of sophisticated implements such as leather-burnishing tools made of animal bone reveal that Neandertals were far more technologically advanced than previously supposed. And evidence that they decorated their bodies with paint, jewelry and feathers attests to Neandertal societies steeped in symbolic traditions once believed to be unique to *H. sapiens*. The notion of Neandertals as doltish cavemen, it turns out, is a canard.

Appropriately enough given the commonalities between anatomically modern humans and the Neandertals, genetic studies have shown that the two groups interbred—frequently enough that genomes of non-African people today are up to 3 percent Neandertal. And because different people carry different bits of Neandertal DNA, the sum total of Neandertal genetic material that persists in modern-day folks is much higher than that: at least 20 percent, according to recent calculations.

The Neandertals were not the only archaic humans with whom *H. sapiens* canoodled. The recently discovered Denisovans—a group identified via DNA recovered from an enigmatic 40,000-year-old finger bone found in a Siberian cave—hooked up with our ancestors, too. Moreover, sex with archaic hominins actually seems to have benefited *H. sapiens,* allowing them to acquire genes that aided their survival: DNA inherited from Neandertals seems to have boosted immunity, for instance. And a gene variant from Denisovans helps Tibetans live at high altitudes.

And yet for all that binds us to our closest evolutionary relatives, some traits clearly set us apart. In this special issue of *Scientific American,* we explore the evolution of those characteristics that make us human—from our upright stance to our peerless ability to collaborate. Our tale has three chapters. The first examines our tangled family tree and the factors that favored the survival of our branch to the exclusion of the others. The second takes stock of how humans differ from other primates and considers how these features may have set us up to thrive. And the third ponders the future of human evolution in a world brimming with technological fixes for everything from loneliness to disease.

We hope you enjoy this story, seven million years in the making. It is not the final word, of course. Just as human evolution seems to be accelerating, so, too, is the pace of paleoanthropological discovery. But we wouldn't have it any other way. SA

***Kate Wong** is a senior editor at* Scientific American. *She served as editor of this single-topic issue.*

WHAT'S INSIDE THIS ISSUE →

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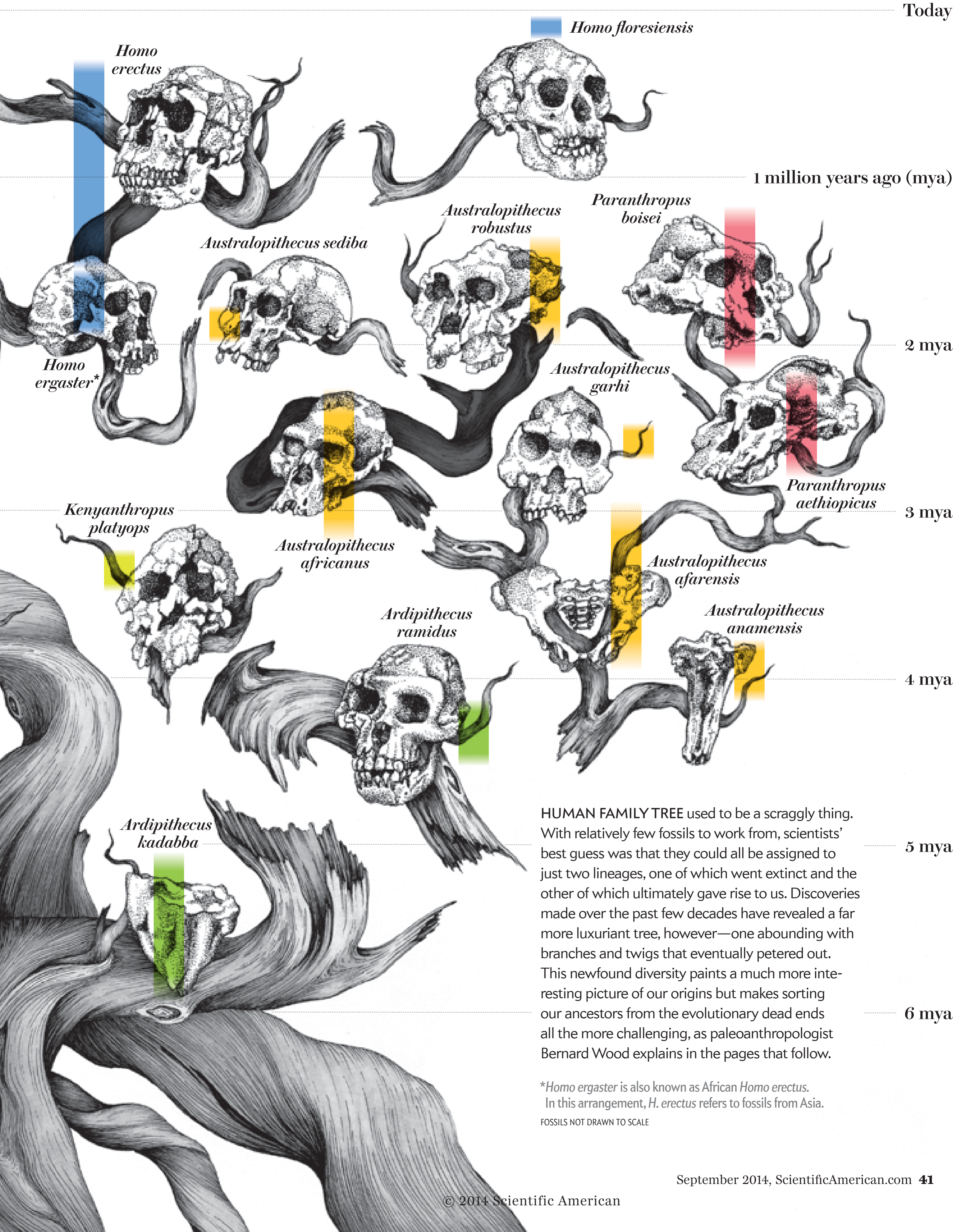
WHERE WE CAME FROM

Illustration by Katy Wiedemann



HUMAN FAMILY TREE used to be a scraggly thing. With relatively few fossils to work from, scientists' best guess was that they could all be assigned to just two lineages, one of which went extinct and the other of which ultimately gave rise to us. Discoveries made over the past few decades have revealed a far more luxuriant tree, however—one abounding with branches and twigs that eventually petered out. This newfound diversity paints a much more interesting picture of our origins but makes sorting our ancestors from the evolutionary dead ends all the more challenging, as paleoanthropologist Bernard Wood explains in the pages that follow.

Homo ergaster is also known as African *Homo erectus*. In this arrangement, *H. erectus* refers to fossils from Asia.

FOSSILS NOT DRAWN TO SCALE

WELCOME TO THE FAMILY

The latest molecular analyses and fossil finds suggest that the story of human evolution is far more complex—and more interesting—than anyone imagined

By Bernard Wood

IN BRIEF

Tracing the evolutionary ancestors of *Homo sapiens* was once thought to be a relatively straightforward matter: *Australopithecus* begat *Homo erectus,* which begat Neandertals, which begat us.

Over the past 40 years fossil finds from East Africa, among other things, have completely shattered that hypothesis.

The latest evidence shows that several different hominin species shared the planet at different times. Figuring out how they are all related—and which ones led directly to us—will keep paleontologists busy for decades to come.

Illustration by Christian Northeast

Bernard Wood is a medically trained paleoanthropologist at George Washington University. His interest in human evolution research began in 1968, when as a medical student, he joined Richard Leakey's expedition to northern Kenya.

So what do you think?” said Lee Berger. He had just opened the lids of two big wooden boxes, each containing the carefully laid out fossilized bones of a humanlike skeleton from Malapa, South Africa. These two individuals, who had drawn their last breath two million years ago, had created quite a stir. Most fossils are “isolated” finds—a jawbone here, a foot bone there. Scientists then have to figure out whether the pieces belong to the same individual. Think of walking down the highway and finding parts of cars—a broken fender here, part of a transmission there. Do they belong to the same model, or even make, of car? Or might they not have come from a car at all but from a pickup?

In contrast, the skeletons from Malapa, though not complete, are intact enough to reduce the possibility of random commingling. Like “Lucy” (unearthed in Ethiopia in 1974) and the “Turkana Boy” (found in Kenya in 1984), they have so much more to say than individual fossils. But they had made the headlines not because they are complete and so well preserved but because Berger, a paleoanthropologist at the University of the Witwatersrand, Johannesburg, had suggested that the individuals were part of a population that was directly ancestral to our own genus, *Homo.*

We all have ancestors. I still have an aged living parent. I had the good fortune to have known all four of my grandparents, and I can even dimly remember three of my great-grandparents. But I also have close relatives who are not ancestors. Not many—my father and I were both only children—but I did have a couple of uncles and aunts. They are an essential part of the family tree of their descendants, but in terms of my family tree they are the equivalent of “optional extras” on an automobile. So Berger wanted me to stop admiring the details of the teeth and jaws and tell him if I thought the Malapa skeletons were the evolutionary equivalent of my parents and grandparents or of my uncles and aunts. In other words, did they belong to a population that was a direct ancestor or just a close relative of modern humans?

When I first started studying human fossils in East Africa nearly 50 years ago, the conventional wisdom was that almost all our extinct close relatives were direct ancestors, and as you went further and further back into the past each was less humanlike and more apelike. But we now know from genetic studies and from fossil evidence of the Neandertals and the so-called Hobbit of Flores, Indonesia (*Homo floresiensis*), that our direct ancestors shared the planet over the past few hundred thousand years with several of our close relatives. Furthermore, other fossil discoveries make it clear that much earlier in

TREASURE TROVE: Researchers in South Africa undertake excavations at the Malapa Cave site (*above*), where two nearly complete skeletons (*shown at left*) of early hominins from two million years ago were recovered.

BRENT STIRTON *Reportage by Getty (skeletons and cave site)*

our prehistory (four million to one million years ago) there were also periods when our ancestors and several close relatives walked the earth at the same time. The presence of multiple evolutionary branches at any one time makes it much more difficult to identify direct ancestors of modern humans than paleontologists anticipated even 20 years ago. Yet the challenge also means that the story of human evolution is far more intricate and fascinating than most of us realized.

A SINGLE BRANCH—OR SEVERAL?

AT THE TIME I entered the field in 1968, Charles Darwin's conception of the Tree of Life held firm sway. He argued that the living world is linked in the same way that the branches of a tree are connected. In Darwin's Tree of Life, all the species alive today sit on the outer surface of the tree, and all the species that are no longer living are located closer to the trunk. Just as each individual modern human must have ancestors, so does each species alive today. In theory, then, the only branches, or lineages, that *must* be in the Tree of Life are the ones that lead from a living species down into the depths of the tree, and the only extinct species that *have* to be within the Tree of Life are the ones situated on those connecting branches; any others represent evolutionary dead ends.

In the case of modern humans and the living apes, this rule means the only branches and species that need to be in our particular part of the tree are the ones that link us to the common ancestor we share with chimpanzees and bonobos—a creature now thought on the basis of molecular evidence to have lived between about eight million and five million years ago.

In the 1960s the outermost branch of the Tree of Life leading to modern humans looked pretty straightforward. At its base was *Australopithecus,* the ape-man that paleoanthropologists had been recovering in southern Africa since the mid-1920s. *Australopithecus,* the thinking went, was replaced by the taller, larger-brained *Homo erectus* from Asia, which spread to Europe and evolved into the Neandertals, which in turn evolved into *Homo sapiens* (aka modern humans). All these were interpreted as direct ancestors of modern humans—the equivalent of my parents, grandparents and great-grandparents. Only one type of hominin (modern humans and any extinct relatives that are more closely related to humans than to chimpanzees or bonobos), called the robust australopiths because of their large jaws and chewing teeth, were surmised to be on a short twig of the human branch and thus the equivalent of my uncle and aunt.

This thinking changed when Louis and Mary Leakey's discoveries of hominins at Olduvai Gorge in Tanzania shifted the focus of research into early hominins that lived more than one million years ago from southern to East Africa. The focus changed not only because the trickle of fossil discoveries in East Africa in the early 1960s turned into a torrent but also because the context of the fossil evidence in East Africa—particularly with respect to its dating—was very different from that in southern Africa.

In the south, the hominin fossils were—and still are—mostly found in caves that form in rocks made of dolomite (a magnesium-rich carbonate). Although researchers occasionally find a well-preserved skeleton of an individual (such as those from Malapa), most of the early hominin fossils found in these caves

were leftovers from the meals of leopards and other predators. These unconsumed bones and teeth were washed into the cave along with soil from the surface. Once inside the cave, the soil and bones formed what are called talus cones. These are untidy versions of the neat cones of sand in the bottom of an old-fashioned egg timer, and the layers, or strata, in the cave do not always follow the general rule that the older layers are at the bottom and the youngest at the top. As if this was not frustrating enough, researchers were until recently at a loss to know how to date the sediments in the caves, and in the early 1960s all investigators could do was fit the hominin finds in a very rough-and-ready time sequence based on the types of fossil animals found in the caves.

In contrast, hominin fossil evidence from East Africa comes from sites close to the Eastern Rift Valley, which slices through this part of Africa from the Red Sea in the north to the shores of Lake Malawi and beyond in the south. Instead of being found in caves, the hominin fossils from East Africa are found in sediments laid down around lakes or along riverbanks. Many of these rock layers preserve the direction of the earth's magnetic field at the time they were laid down, and because they are open-air sites the strata incorporate ash expelled from the many volcanoes generated in and around the Eastern Rift Valley by the movement of tectonic plates. These features mean that at each site researchers have ways of establishing the age of the strata independent of the fossils they contain. In addition, because the layers of volcanic ash function like a series of date-stamped blankets thrown over the region, they allow researchers to correlate fossils deposited thousands of miles apart.

Many of the richest East African hominin fossil sites, such as those in the Omo-Turkana basin and farther north along the Awash River, contain strata that represent millions of years of time. Thus, it is possible to give minimum "start" and "finish" dates for each particular group of fossil hominins. This specificity makes it clear that even within East Africa—let alone between East and southern Africa—there were many times in the past one million to four million years when more than one—and in some periods, several—hominins lived contemporaneously. For example, across a million years (from roughly 2.3 million to 1.4 million years ago), two very different kinds of hominins—*Paranthropus boisei* and *Homo habilis*—lived in the same region of East Africa. They were so different that a prehistoric safari guide would have made the point that their skulls and teeth are almost *never* confused, no matter how fragmentary the fossil evidence. It is also clear that the hominins at the sites in East Africa are different from the ones found in southern Africa—but more on that later.

Finding evidence of *P. boisei* and *H. habilis* in the strata that record thousands of years does not necessarily mean the two hominins had to take turns at the same water hole. But it does mean that one, or perhaps both, of these hominins was not ancestral to modern humans. Although evidence from much later in human evolution is consistent with a small amount of interbreeding between Neandertals and modern humans, in my view the much greater physical differences between *P. boisei* and *H. habilis* indicate that interbreeding was much less likely. And even if it did occur, it did little to blur the substantial differences between these two species. In other words, the image of a single, simple branch no longer seems apt for representing humans a couple of million years ago. Our early ancestry looks more like a bundle of twigs—one might even think it looks like a tangled bush [*see illustration on page 40*].

There is also evidence of multiple lineages in our more recent past. For example, Neandertals have been recognized as a separate species for more than 150 years, and as time goes by researchers discover more and more ways in which they differ from modern humans. We also know that a third hominin, namely *H. erectus,* probably survived much later than was originally thought and that *H. floresiensis,* although it may have been confined to the island of Flores, is almost certainly a fourth hominin that lived on the planet within the past 100,000 years. Evidence of a distinctive fifth hominin, the Denisovans, has come from ancient DNA extracted from a 40,000-year-old finger bone. And evidence has emerged for at least one more "ghost lineage" in the DNA of living modern humans from 100,000 years ago. Thus, our recent evolutionary history is much "bushier" than people thought even 10 years ago.

Perhaps the discovery of bushiness in our evolution should not have been surprising. Contemporary existence of multiple related species seems to have been the rule in the past for many groups of mammals, so why should hominins have been any different? Still, critics of the bushy family tree have charged that paleoanthropologists have been overzealous in identifying new species from their finds—presumably out of a desire for fame and further research funding.

Genetic and fossil evidence shows closely related hominin species shared the planet many times in the past few million years, making it more difficult to identify direct ancestors of modern humans than scientists anticipated even 20 years ago.

My prejudice, on the other hand, is that we are most likely dealing with a real phenomenon. First, there are sound, logical reasons to suspect that the fossil record always underestimates the number of species. Second, we know from living animals that many uncontested species are difficult to distinguish using the bones and teeth—the so-called hard tissues, which is all that survives into the fossil record. Furthermore, most of the mammal species that were living between three million and one million years ago have no direct living descendants. Therefore, the existence of several contemporary early hominins with no direct living descendants is not "odd" after all.

If it is true that hominins had rich diversity in their past, it behooves biologists to uncover the evolutionary pressures that

SCIENTIFIC AMERICAN ONLINE Wood talks about where humans originated—Africa, Asia or Europe?—at ScientificAmerican.com/sep2014/wood-origins

TURKANA FIND: Fossilized skull of a young *Homo ergaster* male that lived and died in Kenya 1.6 million years ago.

KEN GARRETT *National Geographic*

triggered it. Climate is one of the obvious candidates. Climates and thus habitats change over time—they show trends, and they oscillate within those trends. By and large over the period we are considering, there is a trend toward cooler and drier conditions, but within that trend the climate oscillates at predictable intervals, so at times it will be hotter and wetter, and at other times it will be cooler and drier. The type of posture, diet and locomotion that worked at one time may not be so successful at another. Another pressure favoring hominin diversity may have been competition among hominins; if two hominins shared a habitat, even in a very general sense, they would have tended to force each other into different survival strategies. This phenomenon, called character displacement, may explain how *H. habilis* and *P. boisei* came to have such different teeth and jaws—with one group favoring tough, fibrous foods such as grasses and the other leaning toward a diet that included softer, but harder to find, fruits plus the occasional meal of meat or bone marrow. Moreover, as hominins evolved different cultures, their different worldviews and practices could have militated against species merging as the result of interbreeding.

In addition to anatomical differences, researchers can now analyze fossils on a molecular level. Yet when it comes to early hominins—for whom we do not yet have genetic evidence—distinguishing the equivalent of my parents, grandparents and great-grandparents from the equivalent of my uncles and aunts remains challenging. Just because two fossils have similarly shaped jaws or teeth does not mean they share a recent evolutionary history. These overlaps can occur because similar ecological challenges prompt similar morphological solutions. By way of illustration, consider an ax design that works as well to cut down gum trees in Australia as it does to fell spruce in northern Europe; Australians and Europeans could well have hit on the same design without one group having introduced it to the other. We also know that morphology is not infinitely evolvable—for any type of animal or plant, there are a finite number of anatomical or physiological solutions to the same ecological challenge. Thus, the discovery of a shared feature in fossils from two species does not necessarily mean that they are direct taxonomic buddies; they could merely be close relatives that have converged on the same physical solution to a similar ecological challenge.

So what does the future hold for identifying our direct ancestors? I am willing to go a step further than supporting the view that many hominin species roamed the planet simultaneously. I predict that the increased hominin diversity that has been identified in the past four million years will be shown to extend back even further. I think this in part because researchers have not been looking as long or as hard for hominins that lived in even earlier times. Consequently, they have explored fewer sites from before four million years than after. Admittedly, the work is hard. Hominins are among the scarcest mammals in the fossil record. You have to sort through a lot of pig and antelope fossils before you can expect to find the occasional hominin. But if we make a concerted effort to find them, they will surely turn up.

Another reason to predict that more early hominin species remain to be discovered: the fossil records of the more common mammals have nearly as many lineages before three million years as they do after that time. Why would we would not expect hominins to show the same pattern? Finally, existing early hominin sites cover no more than 3 percent of the landmass of Africa, probably less. It is unlikely that such a small geographical sample has managed to capture evidence of all the early hominin species that ever lived on that continent.

And yet each new discovery from before four million years most likely will bring even less certainty. The closer you get to the split between the human and the chimpanzee-plus-bonobo lineages, the more difficult it will be to tell a direct human ancestor from a close relative. It will also be harder to be sure that any new species is a hominin rather than an ancestor of chimpanzees and bonobos or even a species belonging to a lineage that has no living representative. If paleoanthropology is challenging and difficult now—and I remain to be convinced that the Malapa skeletons were direct human ancestors—it is only going to get more so in the future. But it is these challenges that make the field so fascinating. SA

MORE TO EXPLORE

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CLIMATE SHOCKS

Swings between wet and dry landscapes pushed some of our ancestors toward modern traits—and killed off others

By Peter B. deMenocal

IN BRIEF

Changes in climate are emerging as elements that shaped human evolution over millions of years, as scientists learn that such alteration coincided with the extinction of some of our ancestors and the success of others.

Evidence from ancient soils in East Africa, deep-sea sediments and fossil teeth from our forerunners combines to reveal rapid swings between wet and dry environments, as well as two distinct periods when grasslands replaced more wooded areas.

The emergence of our own genus, *Homo*, our varied diet, advances in stone tool technology and the very human trait of adaptability in the face of ongoing change may be tied to these episodes, according to one theory.

SCRAMBLING UP THE STEEP BANK OF A SMALL WADI, OR GULLY, NEAR THE western shore of Lake Turkana in northern Kenya, I stop on a little knoll that offers a view across the vast, mostly barren desert landscape. The glittering, jade-blue lake contrasts in every way with the red-brown landscape around it. This long, narrow desert sea, nestled within Africa's Great Rift Valley, owes its exis-

AMID THE DESERTS of East Africa, Lake Turkana has swelled and disappeared dozens of times while our ancestors were evolving here.

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tence to the Omo River, whose winding flow delivers runoff that comes from summer monsoon rains in the Ethiopian highlands, hundreds of miles north.

The heat here has to be respected. By noon it feels like a blast furnace. The sun beats down, and the hot, stony ground fires it back upward. Scanning the dusty horizon, with the lake winking in the distance, I find it hard to imagine this place as anything but a desert.

Yet evidence for much wetter times is everywhere. Indeed, the little hillock under my boots is a thick chunk of ancient lake sediments that date back 3.6 million years, when a much larger and deeper Lake Turkana filled this basin to the brim. The glassy remains of fossil lake algae make up white, sandy layers, and large fish fossils are common. At times in the past, this rocky desert was carpeted with grasslands and trees and lakes.

Such climate changes may have played a big role in shaping human evolution, a growing number of scientists believe. The Lake Turkana region, together with other sites in East and South Africa, possesses most of the fossil record of early human origins and our evolutionary journey since our lineage split from African apes more than seven million years ago.

Remarkably, major shifts in African climate coincide with two moments on that ancestral path, roughly a million years apart, that mark significant changes in our family tree. The first evolutionary shake-up happened between 2.9 million and 2.4 million years ago. The famous ancestral lineage of "Lucy" and her ilk (*Australopithecus afarensis*) became extinct, and two other, quite distinctive groups appeared. One of them had the hints of some modern-looking traits, including larger brains. Their owners were the very first members of our own genus, *Homo*. The first crude stone tools apppeared near these fossils. The other group besides *Homo* that emerged at this time looked different: a stoutly built, heavy-jawed and ultimately unsuccessful lineage known collectively as *Paranthropus*.

The second shakeup occurred between 1.9 million and 1.6 million years ago. An even larger-brained and more carnivorous species, *Homo erectus* (called *Homo ergaster* by some scientists), appeared on the scene. Its taller, more lithe skeleton was nearly indistinguishable from that of modern humans. This species was also the first to leave Africa to populate Southeast Asia and Europe. Stone tool technology also got a major upgrade: the first hand axes showed up, with large blades carefully shaped on two sides.

Why were these evolutionary milestones, harbingers of modern humanity, so clustered in time? A number of scientists now think two episodes of climate change may have been the cause. These two ecological jolts, coming after long periods of extremely gradual change, moved the cradle of humanity toward increasingly dry and open grasslands. While these broader shifts were happening, the climate whipsawed rapidly between wet and dry periods, so to thrive, our ancestors had to adapt to rapidly changing landscapes.

The evidence comes from an array of new data that tell us how and why African climate and vegetation changed during these big human evolutionary moments. Scientists are now able to extract and analyze molecular remnants of ancient African vegetation from layers of sediments such as the ones I stood on. Chemical analyses of our ancestors' teeth reveal what they ate as the landscape changed. The creatures that adapted to these shifts—those that showed flexibility in what they ate and where they lived—appear to be the ones that prospered. This emphasis on flexibility in the face of new environmental challenges seems to be a trait that carries forward in the human lineage. Other forebears, who did not appear to change with the times, died out. Rick Potts, a paleoanthropologist at the Smithsonian Institution, calls the role of flexibility in making us what we are "variability selection."

LIFE SHAPED BY CLIMATE

THEORIES LINKING CLIMATE CHANGE and evolution go back to Charles Darwin. His premise was that large-scale shifts in climate can shake up the kinds of food, shelter and other resources available in a given region. The disappearance of a favorite food or the replacement of a long wet season with a longer dry one create pressures that lead, eventually, to adaptation, extinction or evolution into different species. The environment, set by climate, will favor creatures with genes for certain advantageous traits, such as larger brains. Over time, those creatures and the genes they carry will come to dominate because more of them will survive. In *On the Origin of Species,* Darwin noted that seasons of extreme cold or drought were effective checks on species numbers.

This process of change is not always subtle or gentle. Each of the "big five" mass extinctions over the fossil record of life on earth during the past 540 million years was accompanied by an environmental disruption. During each of these events, between 50 and 90 percent of all species perished, but this was followed by bursts of new, very different species. These episodes define the major chapters in the history book of life, when new biotic worlds emerged and flourished. We mammals owe a debt of gratitude to the Manhattan-size meteorite that struck the Yucatán Peninsula in what is now Mexico about 66 million years ago. It killed off the dinosaurs (and numerous other less charismatic species), ushering in the rapid radiation and diversification of mammals.

One group of those mammals led, after many more branchings and a lot of time, to us. For these hominins (modern humans and our extinct relatives), scientists have tried out several ideas about the way the environment shaped evolution. The "savanna hypothesis" was one. In its earliest incarnation, scientists proposed that our early human ancestors, with burgeoning bipedality, large brains and toolmaking, were better suited to rapidly expanding savanna grasslands, where competition for resources was fiercer, and they left our apelike forebears behind in receding forests.

This dated view, which still shows up in some textbooks, is incorrect. There was no one-time habitat switch from forests to grasslands but rather a rapid succession of wet-dry cycles that moved, in distinct steps, toward drier conditions. Also, we did not acquire human traits in one single moment but rather in a series of concentrated bursts just when the environment was shifting.

STONE AGE EATING: A distant ancestor, *Paranthropus boisei* (*left*), lived in open plains and mostly ate grasses or related foods, as indicated by chemical analysis of fossil teeth. But *Homo erectus*, sometimes called *Homo ergaster* (*right*), a member of our own genus that lived in the same landscape, had a more varied diet, and adaptability may have helped its evolutionary success.

RECONSTRUCTION AND PHOTOGRAPH © 2014 JOHN GURCHE (*left*); FROM *SHAPING HUMANITY*, BY JOHN GURCHE; YALE UNIVERSITY PRESS, 2013 (*right*)

WET AND DRY CYCLES

EVIDENCE FOR THESE BURSTS of landscape change and evolution comes not just from land but from the sea. African ground sediments are often hard to analyze because of erosion and other geologic disturbances. In the deep oceans, however, they remain undisturbed. By drilling into the seafloor near the African coasts, geologists like myself have been able to penetrate a multimillion-year time capsule, recovering long cores of sediments that preserve complete records of past African environments. To get these cores, we need a special ship. That is why a team of 27 scientists and I spent two months in the fall of 1987 on the 470-foot drilling vessel *JOIDES Resolution*.

"Core on deck!" squawked the driller over the PA system in his Texan twang. We scientists groaned, donned our hard hats, and marched out of the ship's cool, comfortable laboratories into the blinding Arabian sun to carry yet another 30-foot segment of deep-sea sediment core inside for analysis. The *Resolution* is an internationally funded research ship designed to explore and drill the ocean bottom and recover the earth's history recorded there. We were drilling through layers of deep-sea sediment in the Arabian Sea in a mile and a half of water, taking cores nearly half a mile into the sea bottom. Since the divergence of great ape and human lineages several million years ago, the ocean bottom here had accumulated nearly 1,000 feet of deep-sea mud in the dark, peaceful abyss, at a rate of about one and a half inches every 1,000 years.

The sediments here consist of mixtures of fine-white calcium carbonate fossil shells from ancient ocean plankton and darker, silty grains of dirt blown from areas of Africa and Arabia by windy monsoons. When the mix looks darker and gritty, it indicates drier, dustier times. When it looks lighter, that reflects wetter, more humid conditions.

Laying the split sediment core on a table inside the ship's spacious research labs, we could see that the alternating light and dark layers repeated every three feet, more or less, which meant they changed about every 23,000 years. It was clear that African climate history had been one of continuous swings between wetter and drier times. That was nothing like a single, sharp shift to a savanna.

These swings reflected the known sensitivity of African and Asian monsoonal climates to the earth's orbital wobble, which occurs as a regular 23,000-year cycle. The wobble changes the amount of sunlight hitting our planet in a given season. For North Africa and South Asia, more or less heat during the summer increased or decreased monsoon rainfall, making these regions either much wetter or drier as our planet wobbled back and forth.

Just how wet things got is recorded in magnificent rock art drawn between 10,000 and 5,000 years ago by humans during the most recent wet period in North Africa. Art found across the Sahara depicts lush landscapes filled with elephants, hippopotamuses, giraffes, crocodiles and bands of hunters chasing gazelles. The Sahara was covered with grass and trees; lake basins, now overrun by sand dunes, were filled to the brim with water. A swollen Nile River rushed into the eastern Mediterranean, and black, organic-rich sediments called sapropels accumulated on the Mediterranean seafloor. They alternated with whiter layers laid down during dry periods, a bar-code message telling of African climate cycles reaching deep into the past, just like the changing dust layers recovered from the Arabian Sea.

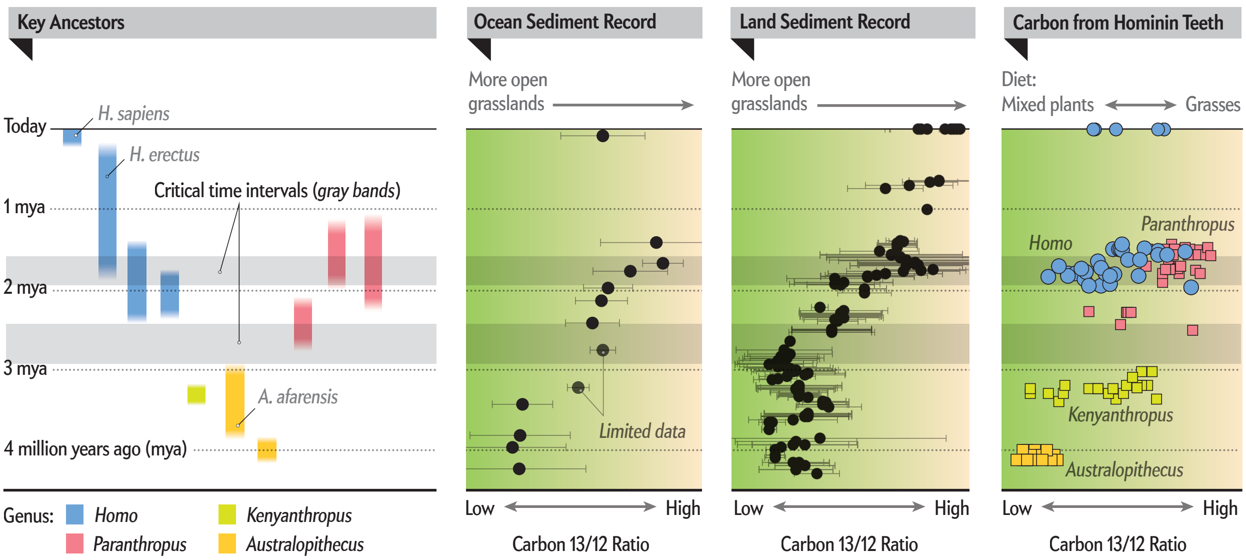
THE LAST OF LUCY

SUPERIMPOSED ON THESE orbital wet-dry cycles were larger steps toward dry and open grasslands. Small patches of grasslands first expanded in East Africa nearly eight million years ago. But

FINDINGS

A Climate for Change

Two moments in our evolutionary history show a tantalizing connection between climate swings and the life and death of key members of our family tree. Starting just after three million years ago, the species *Australopithecus afarensis* vanished, and the groups *Paranthropus* and *Homo* (our own genus) appeared. During this period, changes in carbon isotope ratios from land and ocean sediments show dry grasslands rapidly expanded and wetter woodlands shrank. Starting after two million years ago, *Homo erectus,* one of our direct ancestors, appeared and migrated out of Africa. Again, the carbon evidence shows grasslands got another boost. Yet carbon in the teeth from *H. erectus* indicates the consumption of a mixed diet and an ability to find food from a variety of sources even as grasslands enlarged. *Paranthropus* teeth, however, showed the group (like an earlier extinct forebear, *Kenyanthropus*) was restricted to eating from grassy surroundings.



vast grassy plains such as the Serengeti were only established permanently after three million years ago. Just about this time, our evolutionary history was given a jolt as well.

We lost Lucy. Her extremely successful species, *A. afarensis,* had survived in East Africa for 900,000 years, starting at about 3.9 million years ago. But just under three million years ago, Lucy's kind disappeared from the fossil record.

Next the *Paranthropus* group appeared, followed 2.6 million years ago by the first signs of stone choppers and scrapers and then in a few hundred thousand years by early *Homo* fossils.

We know these changes in our family tree and in technological invention happened during a shift in overall climate because of some clever scientific detective work, tracing the fingerprints left by some plants that flourished in wetter environments and others that thrived in drier times.

Savannas are open tropical ecosystems composed of grasses and sedges, sometimes spotted with clusters of woody trees. Savanna grasses do very well in hot, dry regions because, to take up carbon from the atmosphere, they use a specific photosynthetic pathway called C4. This set of reactions is miserly with carbon and water, an adaptation to life in dry and low-CO_2 environments. Woody vegetation such as trees finds homes in wetter ecosystems because it uses another photosynthetic pathway called C3, which requires much more water.

Thure E. Cerling and his colleagues at the University of Utah developed a way to reconstruct the vegetation history of ancient landscapes. Some years ago researchers discovered that C4 grasses have a greater abundance of the heavier but rarer carbon 13 isotope relative to the lighter, more abundant carbon 12 isotope. But C3 shrubs and woody plants have a lower carbon 13/12 ratio. The scientists discovered that they could take samples of soil or nodules of rock from a given landscape, analyze the carbon ratios, and use them to accurately estimate the percentage of C4 grasses versus C3 woody plants that were once in that area.

When they looked at the East African sediment from sites that had yielded fossil hominins, the researchers learned that East African landscapes were predominantly C3 forest and shrublands before eight million years ago. After that, the proportion of C4 grasslands increased gradually. Then a relatively large and fast shift occurred between three million and two million years ago.

During this shift, grasslands expanded rapidly across present-day Kenya, Ethiopia and Tanzania. The spread was accompanied by a rise in the proportion of grazing mammals, shown by their abundant fossils. As time ticked forward, closer to two million years ago, African antelopes—their horns, whose different shapes indicate different species, are well preserved—seem to have undergone extensive speciation, extinction and adaptation, rather like our hominin forebears.

SOURCE: PETER deMENOCAL

Bovids, the family to which these even-toed ungulates belong, represent roughly one third of all African fossils. Thus, they provide a much larger data set than do the much scarcer hominins. Paleontologist Elisabeth Vrba of Yale University conducted an all-Africa analysis of bovid evolution spanning the past six million years. Her study identified specific times when rates of bovid speciation and extinction were well above normal background levels. The two largest of these events occurred near 2.8 million and 1.8 million years ago, coinciding with the periods of grassland growth that geologists observe, although recent work by René Bobe, now at George Washington University, and Anna K. Behrensmeyer of the Smithsonian Institution suggests these events may be more muted. The anatomy of these fossils hints that some of them were taking advantage of the landscape change. For example, many new grazing bovid species appeared with specialized molars for chewing the abrasive, grassy diet.

DIETS AND LANDSCAPES

AS WAS THE CASE FOR BOVIDS, this vegetation change most likely had a profound effect on our own ancestors because we do not just live in an environment—we eat it. Paleo diet research turns out to be quite useful for understanding how hominins were affected by changing landscapes. Just as isotopes in soils can be used to infer the relative abundance of grasslands in an ancient landscape, scientists have recently started to analyze the isotopic composition in our forerunners' fossil teeth. The carbon isotope analysis of a tooth from a modern American would sit squarely on the C4-grass side of the scale because much of what we consume—meat from cows, soft drinks, snacks, sweets—derives from corn, a C4 grass.

Prehistoric diet changes seem to be part of that second big evolutionary moment in our history, nearly two million years ago, when *Homo* fossils that looked more modern first appeared. Cerling and his many colleagues have been examining the teeth of Turkana Basin fossils. Last year they published a remarkable study that showed a dietary split between early members of our own genus, *Homo,* and members of the heavy-jawed *Paranthropus* group, at just under that two-million-year mark. One species, *Paranthropus boisei,* has sometimes been called Nutcracker Man because of its impressively large molars and massive jawbones. The carbon isotope tooth data from this species indicate it indeed ate a narrow, mostly C4-based diet. Fine microscopic scratches on the teeth, however, suggest it was not cracking nuts at all but rather eating soft C4 grasses and sedges.

The big surprise was for *Homo*. These early teeth recorded a diet that bucked the landscape trend toward greater C4 grass cover. The tooth isotopic data for early *Homo* indicate a strikingly mixed, roughly 65–35 diet of C3- and C4-based foods. It shows that *Homo* sought diverse foods from a landscape that was becoming increasingly uniform. Early *Homo* had a varied, flexible diet and passed its genes to subsequent lineages, eventually leading to us. *Paranthropus,* in contrast, lived in a narrow C4 dietary niche and eventually became extinct.

It is tempting to speculate that the more complex stone tools that first appeared with this group of *Homo*—hand axes, cleavers and the like, tools that required more effort to fashion and could be put to multiple uses—were better suited to help their owners exploit varying food sources. We are still not at all sure what these organisms were eating, but we do know which dietary adaptations were ultimately successful.

FILLING IN THE CLIMATE GAPS

THIS C3/C4 STORY, though intriguing, has some holes in it: in particular, gaps of several thousands of years in land sediment sequences. But again, the ocean sediments and their more complete records can help fill in the blanks. A very promising technique for continuously tracking vegetation changes has emerged in the past decade. All terrestrial plants have waxy leaf coatings that protect them from injury and dehydration. When plants die or become abraded, the waxy coatings are carried by the winds, along with mineral dust and other particles. These coatings are made out of tough little molecules, long carbon-based chains known as lipids. They are resistant to degradation and possess the carbon isotopic signature from their host plant type, C3 or C4. Once chemically isolated from sediments, these plant wax lipids can be measured, and their carbon signature determined as C3 or C4. The relative abundance of a particular type lets us estimate the amounts of grass versus trees and scrubs on ancient landscapes.

Sarah J. Feakins, now at the University of Southern California, and her colleagues applied this technique to reconstruct hominin environments. Analyzing sediments from a drilling site in the Gulf of Aden, she confirmed that East African grasslands expanded between three million and two million years ago, perhaps by as much as 50 percent. Feakins also found that these plant wax biomarkers varied within the dust layers that marked the short-term swings driven by orbital cycles and monsoons. The grasses and woodlands shifted back and forth on this shorter scale, and many of these swings were nearly as large as the long-term shift to more open, grassy landscapes. At the famous fossil site Olduvai Gorge in Tanzania, where hominins lived 1.9 million years ago, scientists Clayton R. Magill and Katherine H. Freeman, both then at Pennsylvania State University, found similar biomarker shifts.

We are closing in on a clearer picture of the how and why of human origins. Gone is the old image of our ancestors emerging from some ancient dark forest to assert dominion over the grassy plains. In its place is new evidence for a series of rapid climate cycles and two large shifts that established the African savanna we know today. Some evidence indicates that our most successful forebears had the flexibility to adapt to these changes. Researchers are already trying to firm up this connection between climate and these evolutionary events with more detailed investigations. Still, it appears as if an answer to the age-old question "How did I get here?" is no longer beyond our reach. SA

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IF I HAD A HAMMER

A radical new take on human evolution adds a large dose of luck to the usual story emphasizing the importance of our forebears' ability to make tools

By Ian Tattersall

IN BRIEF

A new theory credits a combination of cultural advances and unpredictable climate change for the exceptionally fast rate of evolution in early humans.

Climate change repeatedly led to fragmentation of hominin populations, creating small groups in which genetic and cultural novelties were rapidly cemented, accelerating speciation.

Our own species, the anatomically distinctive *Homo sapiens,* was born out of such an event in Africa around 200,000 years ago.

About 100,000 years later an African isolate of our species acquired the ability to use symbols. It was almost certainly this unique symbolic cognition that made it possible to eliminate all hominin competition in little time.

Illustration by Christian Northeast

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WE HUMANS ARE VERY PECULIAR primates. We walk upright, precariously balancing our heavy bodies on two short feet. Our heads are oddly swollen, with tiny faces and small jaws tucked below the front of our balloonlike braincases. Perhaps most remarkably, we process information about the world around us in an entirely unprecedented way. As far as anyone can tell, we are the only organisms that mentally deconstruct our surroundings and our internal experiences into a vocabulary of abstract symbols that we juggle in our minds to produce new versions of reality: we can envision what *might* be, as well as describe what is.

Our predecessors were not so exceptional. The fossil record clearly shows that not much more than seven million years ago, our ancient precursor was an apelike, basically tree-dwelling creature that carried its weight on four limbs and had a large projecting face and powerful jaws hafted in front of a very modest-sized braincase. In all probability, it possessed a cognitive style broadly equivalent to that of a modern chimpanzee. Though undeniably smart, resourceful, and able to recognize and even combine symbols, modern apes do not seem capable of rearranging them to forge new realities. Thus, to arrive at our own species, *Homo sapiens,* from this ancestor took a lot of fast evolutionary modification.

Seven million years may seem like a long time, but it is quick for this kind of transformation. To grasp just how swift the change was, consider that closely related primate species—certainly those in the same genus—typically do not display very different physical or cognitive traits. Moreover, scientists estimate the average longevity of a mammal species at around three million to four million years—about half the time in which the entire hominin group (which includes us and our extinct humanlike relatives) has existed and changed beyond recognition. If evolutionary histories consist of ancestral species giving rise to descendant ones, as we know they do, then the rate of speciation, or introduction of new species, must have sped up dramatically in the human line to account for the radical alterations observed.

Why has evolution in our family been unusually rapid? By what mechanism did this acceleration take place? These are obvious questions and yet, oddly enough, not ones that have greatly interested fossil-oriented students of human evolution. Almost certainly the answer involves our ancestors' ability to meet challenges by producing stone tools, clothing, shelter, fire, and so forth—objects referred to as material culture because they reflect how their users lived. Scientists have long held that natural selection favored those early humans who were best able to innovate and share their cultural know-how. More capable individuals survived and reproduced the most, leading to steady advancements among hominins as a whole.

But this sort of refinement, one generation at a time, would not have been fast enough to radically reshape the human line in seven million years. As we learn more about climate shifts during the past two million years, a new picture is emerging, in which dramatic climate fluctuations acted in tandem with material culture to quicken the evolutionary pace among our forebears. It seems likely that tools and other technologies allowed early hominins to launch themselves into new environments, although when conditions periodically deteriorated, those aids could no longer guarantee survival. As a result, many populations splintered, allowing genetic and cultural novelties to take root much faster than could have happened in larger groups, leading to rapid evolution. Others simply perished. And the species that ultimately prevailed—us—owed its victory as much to chance occurrences, such as those climate shifts, as to its talents.

A SHIFT TOWARD THE GROUND

DESPITE THE HUGELY IMPORTANT ROLE material culture has played in generating the rather extraordinary phenomenon that is *H. sapiens* today, it made a relatively late appearance in our evolutionary story. More than four million years before our ancestors learned to use tools, they first had to quit an existence in the trees and begin to test life on the ground, no small feat for an ape with four grasping extremities. The move would have required an ape that was already in the habit of holding its trunk upright—suspending its considerable body weight from its arms as much as support-

ENGRAVED CHUNK OF OCHER (*left*) from Blombos Cave in South Africa (*below*) is one of two viewed as the earliest clearly symbolic objects, the creation of which seems to distinguish our species from all others. The regularity of the inscribed patterns implies that they encode information.

JOHN READER *Science Source*

ing it with its legs. And indeed, this posture is known to have occurred among some early hominoids—members of the superfamily to which the apes and hominins belong.

Abandoning the trees lies at the origin of our vastly altered anatomy and undeniably set the stage for later adaptations in our lineage, but it did not step up the evolutionary tempo of events. For five million years or so after hominins emerged, they evolved very much like any successful primate group: from the beginning, the human family tree was bushy—meaning there were numerous species occurring at any one time, all testing the new potential that walking on two feet offered. This early experimentation was evidently not of the transformative kind; during this period, all hominins seem to have been variations on the same basic themes, in terms of where and how they lived. As befitted creatures whose lives were distributed between the trees and more open habitats, these ancient human ancestors remained modest in brain and body size and retained archaic body proportions, with short legs and highly mobile arms.

The rate of evolution began to increase dramatically only after the entrance of our genus *Homo* about two million years ago. By at least half a million years before our debut, though, material culture had been born in the form of stone tools, lending strong support to the idea that culture helped to fuel our rapid transformation from a steady succession of tree-dwelling apes to a fast-changing lineup of ground-dwelling humans. Scientists have found primitive stone tools in Africa dating to 2.6 million years ago, and evidence of tool marks on animal bones dates from even earlier. Hominins of the old kind almost certainly made these simple utensils, small, sharp flakes knocked off fist-sized stone cores.

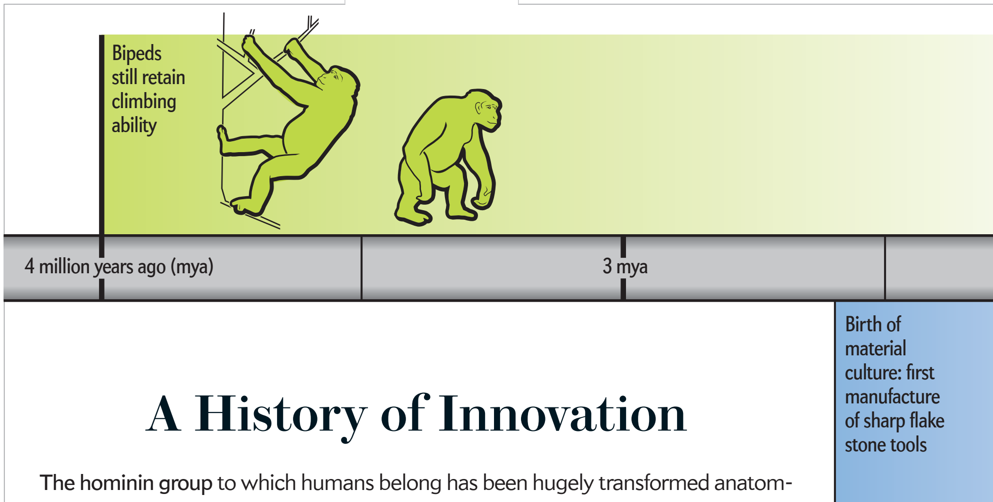
Despite their archaic anatomy, the early toolmakers had moved well beyond the ape cognitive range. Even with intensive coaching, modern apes find it impossible to grasp how to hit one lump of stone with another to detach a flake in the deliberate way used by early hominins. One purpose of such flakes was butchering the carcasses of grazing mammals. This radically new behavior implies that hominin diets had broadened rapidly, from being primarily vegetarian to relying more on animal fats and proteins—though whether by scavenging or by active hunting at this stage is unknown. This richer diet underwrote the later rapid expansion of the energy-hungry brain among members of *Homo*.

Biologists hotly debate over which fossils represent the earliest incarnation of *Homo*, but they agree that the first hominins to possess body proportions basically equivalent to our own appeared less than two million years ago. At about the same time, hominins made their way to many parts of the Old World from Africa. These individuals walked like we do, with an upright, striding gait, lived in the open savanna away from the shelter of the forest and almost certainly ate a diet rich in animal resources. The earliest *Homo* had brains only somewhat larger than those of the early bipeds, but by a million years ago *Homo* species bore brains that had doubled in size, and by 200,000 years ago they had almost doubled again.

ICE AGE ARMS RACE?

THIS RATE OF BRAIN GAIN is amazing by anybody's reckoning and has been identified in at least three independent lineages within *Homo*—namely the one leading to *Homo neanderthalensis* in Europe, to late *Homo erectus* in eastern Asia, and to our own *H. sapiens* in Africa. These parallel trends indicate both that a large brain gave the species involved a survival advantage and that brain enlargement was a common propensity of the genus and not just of the direct lineage to *H. sapiens*. Just conceivably, the tendency hints at an arms race of sorts, as the adoption of projectile weapons made human groups one another's most dangerous

LIFELINE



A History of Innovation

The hominin group to which humans belong has been hugely transformed anatomically, behaviorally and cognitively over the past four million years. By the beginning of that period, arboreal ancestors had begun experimenting with a more terrestrial way of life. By about 2.6 million years ago, primitive stone tools had appeared; cut marks on mammal bones suggest hominins had begun to butcher carcasses even earlier, inaugurating an increasing reliance on animal proteins. This change in diet ultimately fueled a rapid expansion in brain sizes after the appearance of clearly recognizable representatives of our genus *Homo* roughly two million years ago.

predators even as they competed economically for resources.

The traditional explanation of rapid brain development in hominins, favored by evolutionary psychologists, is known as gene-culture coevolution. This process involves the steady operation of natural selection on successive generations of individuals, with powerful positive feedback between innovation in the biological and cultural spheres. As bigger-brained individuals thrived across successive generations, the population became smarter; in turn, it produced tools and other innovations that helped it adapt even more successfully to its environment. In this model, the inherent interplay between genes and culture within a single gradually transforming lineage of species would have virtually obliged human predecessors to become more intelligent and behaviorally complex and would have predisposed them to faster evolutionary change.

A little thought, however, suggests that there must have been more to it than that. One problem with this scenario is that it assumes that the pressures of natural selection—stresses to which the species were adapting—remained consistent over long periods. But in fact, *Homo* evolved during a period of Ice Ages, when the ice caps periodically advanced to what is now New York City and northern England in the Northern Hemisphere, and the tropical zone experienced periods of extreme aridity. Amid such environmental instabilities, no consistent directional selection pressures could have existed. The more we learn about these climatic oscillations, the more we realize just how unstable the ancient environments of our ancestors must have been. Cores drilled in the ice caps and in seafloor muds reveal that the swings between warmer and dramatically colder conditions became increasingly pronounced after about 1.4 million years ago. The result was that in any one location, resident hominin populations would have needed to react frequently to abruptly changing conditions.

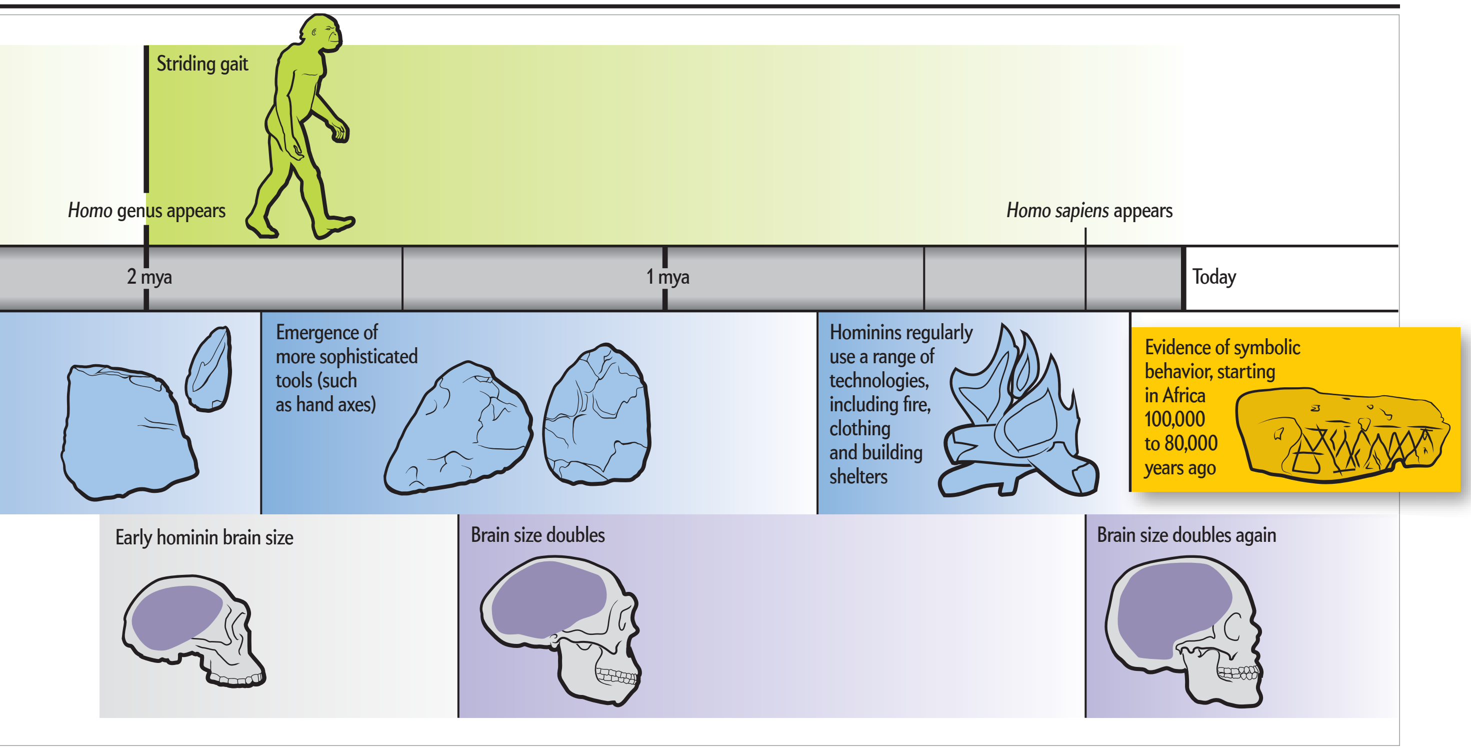
Another problem with the standard explanation has to do with the material record itself. Instead of showing a pattern of steadily increasing technological complexity over the past two million years, archaeological finds suggest that innovation appeared highly sporadically. New types of implements, for example, were typically introduced only at intervals of hundreds of thousands or even a million years, with minimal refinement in between. Hominins at this stage seem to have reacted to environmental change by adapting old tools to new uses, rather than by inventing new kinds of tools.

Adding doubt to the notion of gradual evolution is a lack of evidence that hominin cognitive processes were continuously refined over time. Even as larger-brained species of *Homo* made their appearance, older technologies and ways of life persisted; newer ways of doing things typically came about intermittently and not with the introduction of new species but during the tenure of existing ones. Most notably, evidence of distinctively modern symbolic cognition emerged rather suddenly and only very late indeed. The earliest overtly symbolic objects—two smoothed ocher plaques with geometric engraving—show up at Blombos Cave in South Africa about 77,000 years ago, significantly after anatomically recognizable *H. sapiens* had entered the scene (some 200,000 years ago) [*see box above*]. Because the patterns involved are highly regular, researchers feel confident that they are not random but encode information. Such sudden breakthroughs are not the mark of steady intellectual advancement, generation by generation.

SMALL POPULATION POTENTIAL

EVIDENTLY, THEN, we have to look away from processes occurring within individual lineages to explain the rapid change among Ice Age hominins. Yet the same elements implicated in the gene-culture coevolution story—environmental pressures and material culture—may still have been in play. They simply operated rather differently from how the traditional portrayal suggests. To understand how these factors may have interacted to trigger evolutionary change, we must first recognize that a population needs to be small if it is to incorporate any substantial innovation, genetic or cultural. Large, dense populations simply have too much genetic inertia to be nudged consistently in any direction. Small, isolated populations, on the other hand, routinely differentiate.

Today the human population is sedentary, enormous and continuously distributed across all habitable areas of the globe. But in Ice Age times hominins were mobile hunters and gatherers, living off nature's bounty and thinly spread across the Old World. Climate change constantly buffeted these tiny local populations. Temperature and humidity swings, and even fluctuating sea and lake levels, severely affected local resource avail-



ability, altering the vegetation and driving animals elsewhere. Localities often became hostile to hominins, or even uninhabitable, before kinder conditions returned.

By between one million and 500,000 years ago hominins had a range of technologies—from toolmaking to cooking to shelter building—that would have allowed them to exploit the environment more efficiently than earlier species and to transcend purely physiological limitations. These technologies would presumably have permitted Ice Age hominins to substantially broaden the environments they occupied. In good times, technology would have enabled hominin populations to expand and to occupy marginal regions that would otherwise have been unavailable to them. But when climatic conditions deteriorated, as they periodically did, culture would have proved an incomplete buffer against the harsh elements. As a result, many populations would have declined in size and become fragmented.

The resulting small, isolated groups would have presented ideal conditions for both the fixation of genetic and cultural novelties and ensuing speciation. When conditions improved once more, the altered populations would have expanded again and come into contact with others. If speciation had taken place, competition and selective elimination would have likely occurred. If speciation was incomplete or absent, any genetic novelties would have been incorporated into merged populations. Either way, change took place. In the unsettled Ice Age conditions, this process would have repeated many times in quick succession, setting the scene for exceptionally fast evolution, ultimately leveraged by the possession of material culture. When the dust settled, we stood alone, the serendipitous beneficiaries of cognitive advances, cultural innovation and climate changes that allowed us to eliminate or outlast all hominin competition throughout the Old World in an astonishingly short time. Our competitive edge was almost certainly conferred by our acquisition of our unique mode of symbolic thought, which allows us to scheme and plan in unprecedented ways. Interestingly, this development seems to have occurred within the tenure of our species *H. sapiens,* evidently spurred by a cultural stimulus, quite plausibly the invention of language, which is the ultimate symbolic activity.

This perspective on our evolution, in which our admittedly remarkable species emerged from a rapid sequence of random external events entirely unrelated to our ancestors' specific qualities, is substantially less exalting than the traditional idea of stately improvement over the eons. But a close look at the product makes this entirely plausible: it does not take much introspection to realize that, for all its impressive qualities, *H. sapiens* is a hugely unperfected species—a subject on which volumes have already been written, not least by evolutionary psychologists.

Seeing our amazing species as an evolutionary accident, though, contains a profound lesson. For if we were not shaped by evolution to be something specific—fitted to our environment and tailored to a purpose—then we have free will in a way that other species do not. We can indeed make choices about the ways in which we behave. And this means, of course, that we must accept responsibility for those choices. SA

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Illustration by Portia Sloan Rollings

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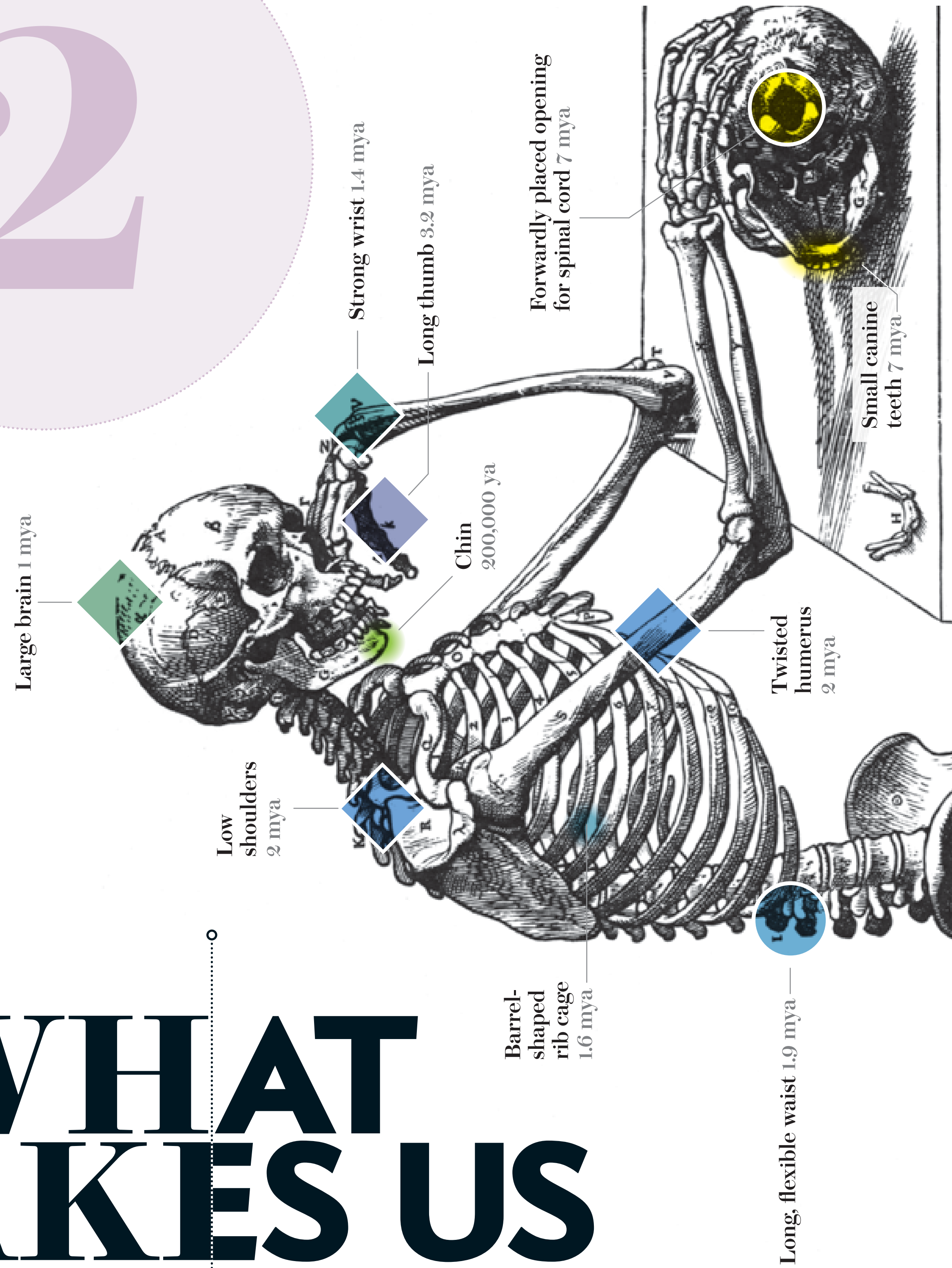
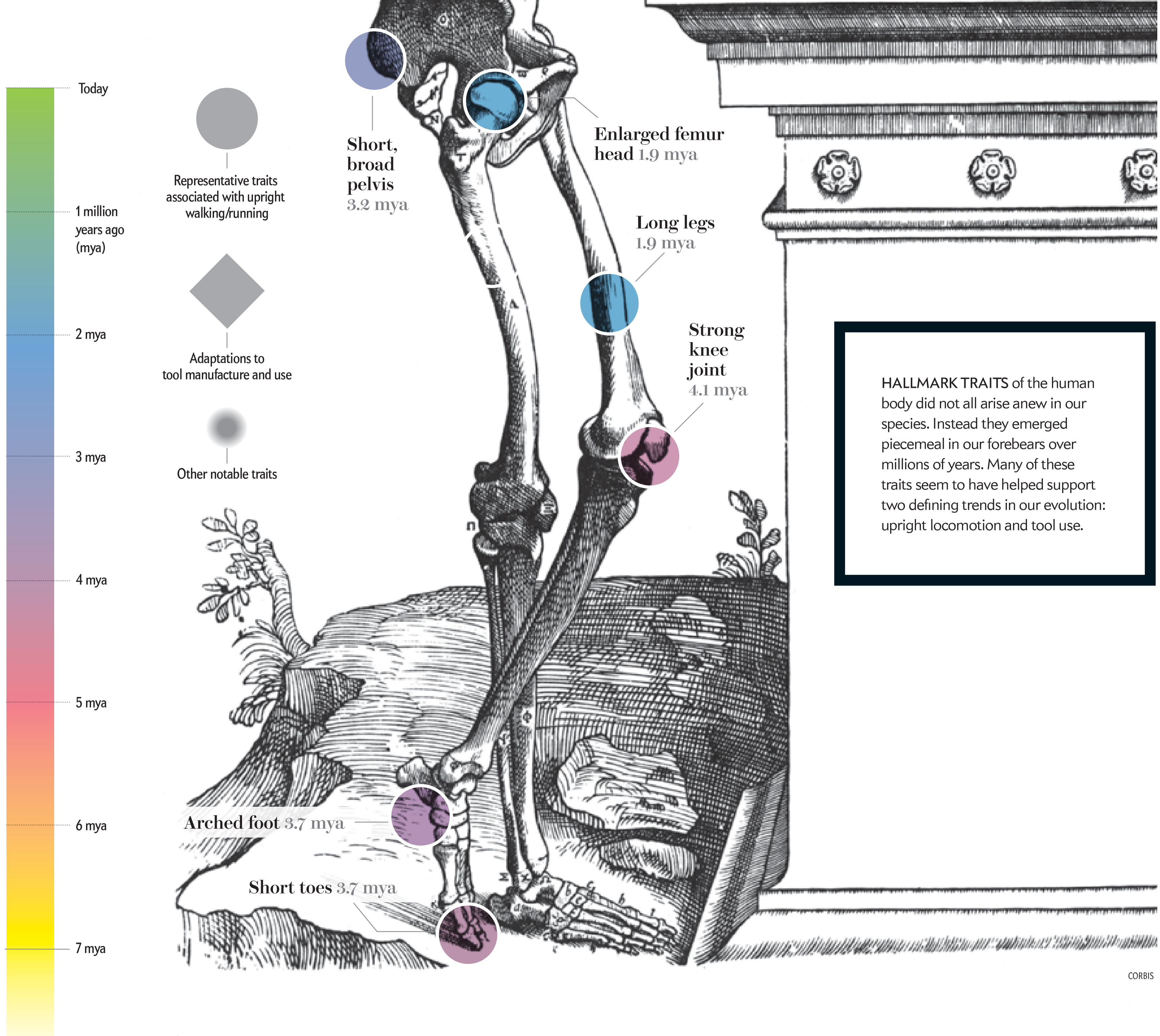


WHAT MAKES US SPECIAL



HALLMARK TRAITS of the human body did not all arise anew in our species. Instead they emerged piecemeal in our forebears over millions of years. Many of these traits seem to have helped support two defining trends in our evolution: upright locomotion and tool use.

CORBIS


Bonding
Partnership
Kinship

POWERS OF TWO

Coupling up might have been the best move our ancestors ever made

By Blake Edgar

IN BRIEF

Even in societies where polygamy is permitted, monogamy is by far the most common human mating arrangement. In this regard, we are unusual animals: fewer than 10 percent of mammals form exclusive sexual relationships.

How humans got this way has been the subject of scientific debate for decades, and it is still an open question. But new research is clarifying matters.

We now know that the first hominins, which emerged more than seven million years ago, might have been monogamous. Humans stayed (mostly) monogamous for good reason: it helped them evolve into the big-brained world conquerors they are today.

Illustration by Martin O'Neill

Blake Edgar is co-author of *From Lucy to Language* and other books and a contributing editor at *Archaeology Magazine*. He is a senior acquisitions editor at the University of California Press.

MAMMALS ARE NOT BIG ON MONOGAMY. IN FEWER THAN 10 PERCENT of species is it common for two individuals to mate exclusively. The primate wing of the group is only slightly more prone to pairing off. Although 15 to 29 percent of primate species favor living together as couples, far fewer commit to monogamy as humans know it—an exclusive sexual partnership between two individuals.

Humans obviously have an imperfect track record. People have affairs, get divorced and, in some cultures, marry multiple mates. In fact, polygamy appears in most of the world's societies. Yet even where polygamy is permitted, it is the minority arrangement. Most human societies are organized around the assumption that a large fraction of the population will pair off into enduring, sexually exclusive couples. And monogamy seems to have done our species good. "Pair bonds," as scientists call monogamous relationships, were a crucial adaptation that arose in an archaic forebear that became central to human social systems and our evolutionary success. "We have a very big advantage over many other species by having pair bonds," says University of Montreal anthropologist Bernard Chapais.

The monogamous couple also forms the basis for something uniquely human—the vast, complex social networks in which we live. Other primate young establish kinship links only through their mother; humans trace kinship from both parents, broadening each generation's family ties. Among humans, social networks extend to include other families and even unrelated groups in widening ripples of relationships. In Chapais's view, such group ties, along with monogamy, constitute "two of the most consequential features of human society."

Scientists have struggled for decades to understand the origins and implications of human monogamy. Basic questions such as when we started to pair up for life, why it was advantageous and how coupling might have spurred our success as a species remain unresolved and contentious, but new research has brought us closer to solving the mystery.

THE ORIGINS OF COUPLING

IT IS ENTIRELY POSSIBLE that our most distant ancestors were monogamous. Fossil evidence, says anthropologist C. Owen Lovejoy of Kent State University, suggests that monogamy predates even *Ardipithecus ramidus,* the species best known from a 4.4-million-year-old partial female skeleton, nicknamed "Ardi," discovered in the Middle Awash region of Ethiopia. In Lovejoy's hypothesis, soon after the split from the last common ancestor between the great ape and human evolutionary branches more than seven million years ago, our predecessors adopted a transformative trio of behaviors: carrying food in arms freed by bipedal posture, forming pair bonds and concealing external signals of female ovulation. Evolving together, these innovations gave hominins, the tribe that emerged when early humans diverged from chimpanzees, a reproductive edge over apes.

According to this hypothesis, an ancestral polygamous mating system was replaced by pair bonding when lower-ranked hominin males diverted energy from fighting one another toward finding food to bring females as an incentive to mate. Females preferred reliable providers to aggressive competitors and bonded with the better foragers. Eventually females lost the skin swelling or other signs of sexual receptivity that would have attracted different males while their partners were off gathering food.

SILVERBACK male mountain gorilla (*at right*) leads his troop in Rwanda. Gorillas, which are polygamous, live in small groups consisting of one dominant male, multiple female mates and their offspring.

PETER G. VEIT *National Geographic*

For evidence, Lovejoy points to *Ar. ramidus*'s teeth. Compared with living and fossil apes, *Ar. ramidus* shows a stark reduction in the differences between male and female canine-tooth size. Evolution has honed the daggerlike canines of many male primates into formidable weapons used to fight for access to mates. Not so for early hominins. Picture the canines in a male gorilla's gaping jaws; now peer inside your own mouth. Humans of both sexes have small, stubby canines—an unthreatening trait unique to hominins, including the earliest *Ardipithecus* specimens.

A rough correlation also exists between mating behavior in primates and sexual dimorphism—that is, differences in body mass and size between males and females of the same species. The more dimorphic a primate species is, the more likely it is that males fight over females. At one extreme, polygamous gorilla males grow to be more than twice as massive as females. At the opposite extreme, both male and female gibbons, which are mainly monogamous, are nearly equal in mass. Humans lie closer to gibbons on the dimorphism spectrum: human males can be up to 20 percent more massive than females.

There is only so much we can make of the fossil record, though. Paleoanthropologist J. Michael Plavcan of the University of Arkansas urges caution in making the leap from fossilized bones to social behavior in hominins. Consider *Australopithecus afarensis,* the species to which "Lucy" belonged, which lived between 3.9 million and three million years ago. Like *Ardipithecus, A. afarensis* had small canines, but its skeleton displays a level of dimorphism between that of modern chimpanzees and gorillas. "You have [a level of] body-size dimorphism suggesting that [*A. afarensis*] males were competing for females and [a] loss of canine dimorphism that suggests they weren't," Plavcan says. "It's a puzzle."

Many anthropologists also dispute Lovejoy's conclusion that monogamy nurtured by males providing food for their mates and offspring has been a hominin strategy for millions of years. Last year in the journal *Evolutionary Anthropology,* Chapais argued that the unique features of human family and social structure (monogamy, kinship ties through both parents and expanding social circles) emerged in a stepwise sequence. Before the first step, Chapais said, both male and female hominins were, like chimpanzees, promiscuous with partners. Then came a transition to polygamy, which is found in gorillas. But keeping

many mates is hard work. It involves a lot of fighting other males and guarding females. Monogamy might have emerged as the best way to reduce the effort of polygamy.

Chapais declines to speculate about when this shift happened and what species were involved. But other researchers are homing in on the period between two million and 1.5 million years ago, after the origin of our genus *Homo* and coincident with physical changes that show up in *Homo erectus,* most likely the first hominin species to successfully migrate beyond Africa. *H. erectus* possessed a much larger body, proportioned more like that of a modern human, than its predecessors. Roughly twice the size of Lucy's species, *H. erectus* also seems to be less sexually dimorphic than australopithecines and the earliest members of *Homo*. Limited fossil evidence suggests that *H. erectus* females started to approach the physical stature of males and to have a similar degree of dimorphism as in modern humans, which together could suggest that *H. erectus* had a less competitive way of life than its ancestors. Because primates with similar body sizes tend to be monogamous, this change could signal a shift toward more exclusive mating behavior.

AZARA'S OWL MONKEYS of South America are fully monogamous, with the father handling much of the child care.

COURTESY OF MILAN KOŘÍNEK www.biolib.cz/en

A STRATEGIC PARTNERSHIP

IF SCIENTISTS CANNOT AGREE on when humans became monogamous, we can hardly expect them to agree on why it happened. In 2013 two independent research teams published separate statistical studies of existing literature to determine which behaviors could have been drivers of monogamy. Both studies aimed to determine the best explanation for monogamy from three persistent hypotheses, generally known as female spacing, infanticide avoidance and male parental care.

The female-spacing hypothesis posits that monogamy arises after females begin to establish larger territories to gain more access to limited food resources and, in the process, put more distance between one another. With females farther apart, males have a harder time finding and keeping multiple mates. Settling down with a single partner makes life easier, reducing a male's risk of being injured while patrolling his territory and enabling him to ensure that his mate's offspring are his own.

Zoologists Dieter Lukas and Tim Clutton-Brock, both at the University of Cambridge, found evidence for this idea in a statistical analysis of 2,545 species of mammals. They described their findings in a paper published in *Science*. The data indicated to them that mammals started out solitary, but then one species or another switched to monogamy 61 different times during their evolutionary history. Monogamy most frequently emerged in carnivores and primates, suggesting that species will tend toward mating in pairs when its females require a rich but rare diet (such as protein-rich carcasses or ripe fruits) that can usually be obtained only by searching a large area. Their findings provided the strongest statistical support for the conclusion that increasingly scattered, solitary females drove males to solicit single partners.

Lukas acknowledges that although the hypothesis may work for nonhumans, it might not be so apt for humans: it is difficult to reconcile the inherent sociality of humans with a hypothesis that depends on a low density of available females. It may be that our ancestors were too social for females to have been scattered across the savanna like other mammals. But the theory could potentially hold for humans if monogamy arose in hominins before our tendency to dwell in groups did.

The second leading hypothesis holds that monogamy originated from the threat of lethal violence toward offspring. If a rival male challenged or supplanted a dominant male in a community, the usurper could kill infants that he had not sired. Mothers would stop lactating and start ovulating again, giving the marauding male a chance to spread his genes. To prevent infanticide, a female would select a male ally who could defend her and her baby.

Anthropologist Kit Opie of University College London cites evidence for the infanticide-avoidance hypothesis in a study published in the *Proceedings of the National Academy of Sciences USA*. Opie and his colleagues ran computer simulations of primate evolutionary history for 230 primate species; they then applied what is called a Bayesian statistical analysis to determine which of the three prominent hypotheses for the origin of monogamy had the highest probability of being correct. They identified a significant correlation between monogamy in primates and each of the three hypothetical triggers, but only an increase in the threat of infanticide consistently preceded the appearance of monogamy in multiple primate lineages.

The biology and behavior of modern primates add some plausibility to the conclusion that infanticide is a spur to monogamy. Primates are uniquely at risk for infanticide: they have big brains that need time to develop, which leaves babies dependent and vulnerable for long periods after birth. And the killing of babies has been observed in more than 50 primate species; it typically involves a male from outside a group attacking an unweaned infant in a bid for dominance or access to females. But there are limits to the evidence: nearly all these species have either promiscuous or polygamous mating systems, so the distribution of infanticide in living primates does not fit the prediction that monogamy should evolve when infanticide is a big threat.

The third hypothesis for why monogamy evolved highlights a male pulling his weight with parental duties. When a baby becomes too costly in terms of calories and energy for a mother to raise on her own, the father who stays with the family and

SCIENTIFIC AMERICAN ONLINE For more on the mating habits of primates, go to ScientificAmerican.com/sep2014/coupling

provides food or other forms of care increases his offspring's chances of survival and encourages closer ties with the mother. A related idea, proposed by anthropologist Lee Gettler of the University of Notre Dame, holds that the mere carrying of offspring by fathers fosters monogamy. Mothers have to meet the considerable nutritional demands of nursing infants. Yet for primates and human hunter-gatherers, hauling an infant, especially without the benefit of a sling or other restraint, required an expense of energy comparable to breast-feeding. Carrying by males could have freed females to fulfill their own energetic needs by foraging.

South America's Azara's owl monkey may offer some insight into how paternal care would reinforce monogamy. These monkeys live in small family groups, with an adult male-and-female pair and an infant, plus a juvenile or two. A mother monkey carries a newborn on her thigh just after birth. But the baby's father assumes most of the carrying and caretaking—grooming, playing and feeding—from the time the baby is two weeks old. The adult partners literally stay in touch with frequent tail contact, and the male's mere proximity to both the female and his young may promote deeper emotional ties.

Keeping many mates is hard work. It involves a lot of fighting with other males and guarding females. Monogamy might have emerged as a way to reduce that effort.

Indeed, a study published in March in the *Proceedings of the Royal Society B* presented genetic evidence that Azara's owl monkey pairs remain monogamous—the first genetic confirmation for any nonhuman primate. DNA collected from several study groups revealed that all the females and all but one of the males in 17 pairs were the most likely parents of 35 offspring. "They go all the way and commit to a monogamous relationship in genetic terms," says anthropologist Eduardo Fernandez-Duque, now at Yale University and a co-author of the study. Mating bonds between Azara's owl monkeys last an average of nine years, and monkeys that stay with the same partner achieve greater reproductive success—the end game of evolution under any mating system.

What do the two recent statistical studies have to say about the paternal care hypothesis? Both concluded that paternal care seemed the least likely among the competing hypotheses to trigger monogamous mating—but, Lukas says, "paternal care may still explain why a species *stays* monogamous."

IT TAKES A VILLAGE

A MONOGAMOUS SET OF PARENTS is not enough to raise an ape as smart and social as a human, says anthropologist Sarah Hrdy of the University of California, Davis. A human baby consumes some 13 million calories on its long journey from birth to maturity, a heavy burden for a mother to bear even with a mate helping. This demand might explain why in many societies, human mothers rely on "alloparents" (such as the kin of either parent or other group members) to help provide food and child care. "Human mothers are willing to let others hold their babies right from birth," Hrdy notes. "That's amazing, and it's remarkably unapelike." No ape engages in anything like alloparenting.

Hrdy maintains that cooperative breeding, a social system in which alloparents help care for young, evolved among our ancient ancestors starting with *H. erectus* nearly two million years ago. This species had a much larger body and brain than its ancestors; by one estimate, it took 40 percent more metabolic energy to run an *H. erectus* body relative to previous hominins. If *H. erectus* started down a humanlike path of delayed development and prolonged dependency, cooperative alloparents might have been required to support the energetic demands of raising bigger-brained babies.

Without cooperative breeding, conclude Karin Isler and Carel van Schaik, both at the University of Zurich, early *Homo* would not have broken through the hypothetical "gray ceiling" that constrains an ape's brain to a maximum volume of about 700 cubic centimeters. To pay the energetic cost of having an enlarged brain, an animal must reduce its rate of birth or its rate of growth, or both. But humans have achieved shorter weaning periods and greater reproductive success than a creature with a brain volume ranging from 1,100 to 1,700 cm^3 should have been able to. Isler and van Schaik attribute this success to alloparenting, which enabled *H. erectus* to have offspring more frequently while providing those offspring enough energy to grow a large brain.

It was cooperation, then, whether in the form of monogamous pairs, nuclear families or tribes, that enabled humans to succeed when all our fossil ancestors and cousins went extinct. In fact, cooperation may be the greatest skill we have acquired during the past two million years—one that enabled our young genus to survive through periods of environmental change and stress and one that may well determine our geologically young species' future. SA

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ONE FOR ALL

Our ability to cooperate in large societies has deep evolutionary roots in the animal kingdom

By Frans de Waal

TRADITIONAL DISCUSSIONS OF HOW HUMANITY BECAME THE DOMINANT form of life, with a population of more than seven billion and counting, have focused on competition. Our ancestors seized land, so the story goes, wiped out other species—including our brethren the Neandertals—and hunted big predators to extinction. We conquered nature, red in tooth and claw.

Overall, however, this is an unlikely scenario. Our forebears were too small and vulnerable to rule the savanna. They must have lived in constant fear of pack-hunting hyenas, 10 different kinds of big cats and other dangerous animals. We probably owe our success as a species more to our cooperativeness than our capacity for violence.

Our propensity to cooperate has old evolutionary roots. Yet only humans organize into groups capable of achieving colossal feats. Only humans have a complex morality that emphasizes responsibilities to others and is enforced through reputation and punishment. And sometimes we do incredible things that put a lie to the idea of humans as purely self-interested actors.

Consider this scene that unfolded last year in a Metrorail station in Washington, D.C. A passenger's motor-

Illustration by Martin O'Neill

ized wheelchair malfunctioned, and the man ended up sprawled on the tracks. Within seconds, multiple bystanders jumped down to bring him back up before the next train. An even more dramatic rescue occurred in 2007 in the New York City subway, when Wesley Autrey, a 50-year-old construction worker, saved a man who had fallen in front of an approaching train. Too late to pull him up, Autrey jumped between the tracks and lay on top of the other man while five cars rolled overhead. Afterward, he downplayed his heroism: "I don't feel like I did something spectacular."

What he did was spectacular, of course. But what propelled him to put his own life in jeopardy to help a fellow stranger in the subway? For answers to this question and to how we came to cooperate in other ways, we must first look at similar behavior in our evolutionary cousins, particularly our closest living relatives: chimpanzees and bonobos.

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WHALE SHARERS: **Lamaleran hunters, who work together in life or death situations, possess an acute sense of fairness.**

PRIMATE COOPERATION

I REGULARLY WATCH less dramatic cases of selfless cooperation in these animals at the Yerkes National Primate Research Center at Emory University. My office overlooks a large, grassy enclosure, in which an aging female, Peony, spends her days in the sun with other chimpanzees. Whenever her arthritis flares up, she has trouble walking and climbing. But while Peony is huffing and puffing to get up into the climbing frame, an unrelated younger female may move behind her, place both hands on her ample behind and push her up. We have also seen others bring water to Peony, for whom the walk to the spigot is strenuous. When she starts out in that direction, others run ahead to pick up a mouthful of water, then stand in front of the old lady, who opens her mouth to let them spit a jet of water into it.

A host of recent studies have carefully documented primate cooperation, reaching three main conclusions. First, cooperation does not require family ties. Even though these animals favor kin, they do not limit their cooperation to family. DNA extracted from chimpanzee feces collected in the African forest has allowed field-workers to examine which animals hunt and travel together. Most close partnerships in the forest involve unrelated individuals. Friends mutually groom one another, warn each other of predators and share food. We know the same is true for bonobos.

Second, cooperation is often based on reciprocity. Experiments indicate that chimpanzees remember received favors. One study measured grooming in a captive colony in the morning before feeding time. On introduction of sharable food, such as watermelons, the few lucky possessors would be surrounded by beggars holding out a hand, whimpering and whining. Researchers found that an individual that earlier in the day had groomed another was more likely to obtain a share from this partner later on.

Third, cooperation may be motivated by empathy, a characteristic of all mammals, from rodents to primates. We identify with others in need, pain or distress. This identification arouses emotions that tend to prompt helping action. Scientists now believe that primates, in particular, go further and care about the well-being of others. In a typical experiment, two monkeys are placed side by side, while one of them selects a token based on color. One color rewards only the monkey itself but the other rewards both of them. After a few rounds, the choosing monkey opts most often for the "prosocial" token. This preference is not based on fear of the other monkey, because dominant monkeys (which have the least to fear) are the most generous.

Sometimes caring about others costs primates nothing, such as in the above test, but they also help one another at a substantial cost, such as when they lose half their food in the process. In nature, chimpanzees are known to adopt orphans or defend others against leopards—both extremely costly forms of altruism.

DEEPER ROOTS OF HELPING

THESE CARING TENDENCIES in primates probably evolved from the obligatory maternal care demanded of all mammals. Whether a mouse or an elephant, mothers need to respond to their young's

IN BRIEF

Human beings have a unique ability to cooperate in large, well-organized groups and employ a complex morality that relies on reputation and punishment.

But much of the foundation for this cooperation—including empathy and altruism—can also be observed in our primate cousins.

Homo sapiens' unique cooperative abilities are what have allowed the species to become the dominant one on the earth.

FRED BRUEMMER *Getty Images*

SCIENTIFIC AMERICAN ONLINE View a slide show of animals that help one another at ScientificAmerican.com/sep2014/cooperation

signals of hunger, pain or fear—otherwise the infants might perish. This sensitivity (and the neural and hormonal processes that support it) was then co-opted for other relationships, helping to enhance emotional bonding, empathy and cooperation within the larger society.

Cooperation affords substantial benefits, so it is not surprising that it was co-opted in these ways. The most ubiquitous form in the animal kingdom is known as mutualistic cooperation and is presumably so widespread because it produces immediate payoffs, such as providing food or defending against predators. It is marked by working together toward an obvious goal that is advantageous to all—say when hyenas bring down a wildebeest together or when a dozen pelicans in a semicircle drive fish together with their feet in a shallow lake, which allows them to simultaneously scoop up mouthfuls of prey. Such cooperation rests on well-coordinated action and shared payoffs.

This kind of cooperation can spawn more subtle cooperative behaviors such as sharing. If one hyena or one pelican were to monopolize all rewards, the system would collapse. Survival depends on sharing, which explains why both humans and animals are exquisitely sensitive to fair divisions. Experiments show that monkeys, dogs and some social birds reject rewards inferior to those of a companion performing the same task; chimpanzees and humans go even further by moderating their share of joint rewards to prevent frustration in others. We owe our sense of fairness to a long history of mutualistic cooperation.

THE HUMAN DIFFERENCE

HUMANS PROVIDE SHARP EXAMPLES of how sharing is linked with survival. Lamaleran whale hunters in Indonesia roam the open ocean in large canoes, from which a dozen men capture whales almost bare-handed. The hunters row toward the whale, the harpoonist jumps onto its back to thrust his weapon into it, and then the men stay nearby until the leviathan dies of blood loss. With entire families tied together around a life-threatening activity, their men being literally in the same boat, distribution of the food bonanza is very much on their mind. Not surprisingly, the Lamalera people are the champions of fairness, as measured by anthropologists using a tool called the Ultimatum Game, which measures preferences for equitable offers. In societies with greater self-sufficiency, such as those in which every family tends its own plot of land, equity is less important.

One oft-mentioned difference between humans and other primates is that we are the only species to cooperate with outsiders and strangers. Although our willingness to cooperate depends on the circumstances (after all, we may also kill those who do not belong to our group), primates in nature are mostly competitive between groups. The way human communities allow outsiders to travel through their territories, share meals with them, exchange goods and gifts, or band together against common enemies is not a typical primate pattern.

Yet this openness does not need a special evolutionary explanation, as some have argued. Most likely, cooperation among strangers is an extension of tendencies that arose for in-group use. In nature, it is not unusual for existing capacities to be applied outside their original context, a bit the way primates use hands (which evolved for tree climbing) to cling to their mothers. Experiments in which capuchin monkeys and bonobos interact with unfamiliar outsiders have shown them capable of exchanging favors and sharing food. In other words, the potential for cooperating with outsiders is present in other species even if they rarely encounter situations in nature that prompt them to do so.

One way we may be truly unique, though, is in the highly organized nature of our cooperativeness. We have the capacity to create hierarchical collaborations that can execute large-scale projects of a complexity and magnitude not found elsewhere in nature. Consider the terraced rice paddies of the Mekong Delta—or the technology that went into CERN's Large Hadron Collider.

Most animal cooperation is self-organized in that individuals fulfill roles according to their capacities and the "slots" open to them. Sometimes animals divide roles and closely coordinate, such as when synchronized killer whales make a wave that washes a seal off an ice floe or when several chimpanzee males organize as drivers and blockers to chase a group of monkeys through the canopy, as if they agreed on their roles beforehand. We do not know how the shared intentions and goals of this kind of cooperation are established and communicated, but they do not seem to be orchestrated from above by leaders, as is typical of humans.

Humans also have ways of enforcing cooperation that thus far have not been documented in other animals. Through repeated interactions, we build reputations as reliable friends, or poor ones, and may get punished if our efforts fall short. The potential for punishment also discourages individuals from cheating the system. In the laboratory, humans punish freeloaders, even at a cost to themselves, a practice that, in the long run, would tend to promote cooperation in a population. There is much debate about how typical such punishment is in real life, outside the lab, but we do know that our moral systems include expectations about cooperation and that we are hypersensitive to public opinion. In one experiment, people donated more money to a good cause if a picture of two eyes were mounted on the wall to watch them. Feeling observed, we worry about our reputation.

These concerns over reputation could have been the primordial glue that enabled early *Homo sapiens* to stick together in ever larger societies. During much of human prehistory, our ancestors lived nomadic lives much like current hunter-gatherers. These modern peoples demonstrate a robust potential for peace and trade between communities, which suggests that early *H. sapiens* had these traits, too.

Without denying our violent potential, I am convinced that it is these cooperative tendencies that have brought us as far as we have come. Building on tendencies that evolved in nonhuman primates, we have been able to shape our societies into complex networks of individuals who cooperate with one another in all kinds of ways. SA

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THE "IT"

SKULL OF A HUMAN faces off with a chimpanzee skull (*at right*). Despite divergent brain sizes, chimps have many of the same cognitive abilities as humans, with a few key exceptions.

FACTOR

The capacity to engage in shared tasks such as hunting large game and building cities may be what separated modern humans from our primate cousins

By Gary Stix

Gary Stix is a senior editor at *Scientific American.*

AT A PSYCHOLOGY LABORATORY IN LEIPZIG, GERMANY, TWO TODDLERS eye gummy bears that lie on a board beyond their reach. To get the treats, both tots must pull in tandem on either end of a rope. If only one child pulls, the rope detaches, and they wind up with nothing.

A few miles away, in a plexiglass enclosure at Pongoland, the ape facility at the Leipzig Zoo, researchers repeat the identical experiment, but this time with two chimpanzees. If the primates pass the rope-and-board test, each one gets a fruit treat.

By testing children and chimps in this way, investigators hope to solve a vexing puzzle: Why are humans so successful as a species? *Homo sapiens* and *Pan troglodytes* share almost 99 percent of their genetic material. Why, then, did humans come to populate virtually every corner of the planet—building the Eiffel Tower, Boeing 747s and H-bombs along the way? And why are chimps still foraging for their supper in the dense forests of equatorial Africa, just as their ancestors did seven or so million years ago, when archaic humans and the great apes separated into different species?

As with any event that occurred on the time scale of evolution—hundreds of thousands or millions of years in the making—scientists may never reach a consensus on what really happened. For years the prevailing view was that only humans make and use tools and are capable of reasoning using numbers and other symbols. But that idea fell by the wayside as we learned more about what other primates are capable of. A chimp, with the right coach, can add numbers, operate a computer and light up a cigarette.

At present, the question of why human behavior differs from that of the great apes, and how much, is still a matter of debate. Yet experiments such as the one in Leipzig, under the auspices of the Max Planck Institute for Evolutionary Anthropology, have revealed a compelling possibility, identifying what may be a unique, but easy to overlook, facet of the human cognitive apparatus. From before their first birthday—a milestone some psychologists term “the nine-month revolution”—children begin to show an acute awareness of what goes on inside their mother’s and father’s heads. They evince this new ability by following their parents’ gaze or looking where they point. Chimps can also figure out what is going on in a companion’s mind to some degree, but humans take it one step further: infant and elder also have the ability to put their heads together to focus on what must be done to carry out a shared task. The simple act of adult and infant rolling a ball back and forth is enabled by this subtle cognitive advantage.

Some psychologists and anthropologists think that this melding of minds may have been a pivotal event that occurred hundreds of thousands of years ago and that shaped later human evolution. The ability of small bands of hunter-gatherers to work together in harmony ultimately set off a cascade of cognitive changes that led to the development of language and the spread of diverse human cultures across the globe.

This account of human psychological evolution, synthesized from bits and pieces of research on children and chimps, is speculative, and it has its doubters. But it provides perhaps the most impressively broad-ranging picture of the origins of cognitive abilities that make humans special.

THE RATCHET EFFECT

THE MAX PLANCK INSTITUTE maintains the world’s largest research facility devoted to examining the differences in behavior between humans and the great apes. Dozens of studies may be running at any one time. Researchers can draw subjects from a database of more than 20,000 children and recruit chimpan-

IN BRIEF

Humans—it was once thought—differed from other animals by their use of tools and their overall superiority in a range of cognitive abilities. Close observation of the behaviors of chimpanzees and other great apes has proved these ideas to be wrong.

Chimpanzees score as highly as young children on tests of general reasoning abilities but lack many of the social skills that come naturally to their human cousins. Unlike humans, chimps do not collaborate in the large groups needed to build complex societies.

Comparison of human and chimp psychology reveals that an essential source of the differences in humans may be the evolution of the ability to intuit what another person is thinking so that both can work toward a shared goal.

PRECEDING PAGES: INGO ARNDT *Getty Images*

EYES ON THE PRIZE: Both children and chimpanzees sometimes undergo the same tests to compare how closely members of each species work with one another. The two partners must cooperate by pulling each rope in unison to get a treat—either gummy bears in a child laboratory at the Max Planck Institute or bananas or other fruit at the nearby zoo. If one team member pulls and the other does not, the rope comes free, and the pair go hungry.

Photographs by Daniel Rosenthal

zees or members of any of the other great ape species—orangutans, bonobos and gorillas—from the Wolfgang Köhler Primate Research Center at the Leipzig Zoo a few miles away.

The institute began 17 years ago, seven years after the reunification of Germany. Founding the institute required coming to grips with the tarnished legacy of German anthropology—and its association with Nazi racial theories and, in particular, the grisly human experiments performed in Auschwitz by Josef Mengele, who was a physician with a doctorate in anthropology. The institute's organizers went out of their way to recruit group leaders for genetics, primatology, linguistics and other disciplines who were not native Germans.

One of them was Michael Tomasello, a tall, bearded psychologist and primatologist. Now 64, he grew up in a small citrus-growing city at the epicenter of the Florida peninsula. He began his academic career at the University of Georgia with a dissertation on the way toddlers acquire language. While he was doing his doctorate in the 1970s, linguists and psychologists often cited language as exhibit number one for human exceptionalism in the animal world.

Tomasello's doctoral thesis chronicled how his almost two-year-old daughter learned her first verbs. The emergence of proto words—"play play" or "ni ni"—revealed a natural inclination of the young child to engage in trial-and-error testing of language elements, an exercise that gradually took on the more conventional structuring of grammar and syntax. This learning process stood in contrast to the ideas of Noam Chomsky and other linguists who contended that grammar is somehow genetically hardwired in our brains—an explanation that struck Tomasello as reductionist. "Language is such a complicated thing that it couldn't have evolved like the opposable thumb," he says.

His work on language broadened his thinking about the relation between culture and human evolution. Tomasello realized that selective forces alone, acting on physical traits, could not explain the emergence of complex tools, language, mathematics and elaborate social institutions in the comparatively brief interval on the evolutionary time line since humans and chimps parted ways. Some innate mental capacity displayed by hominins (modern humans and our extinct relatives) but absent in nonhuman primates must have enabled our forebears to behave in ways that vastly hastened the ability to feed and clothe themselves and to flourish in any environment, no matter how forbidding.

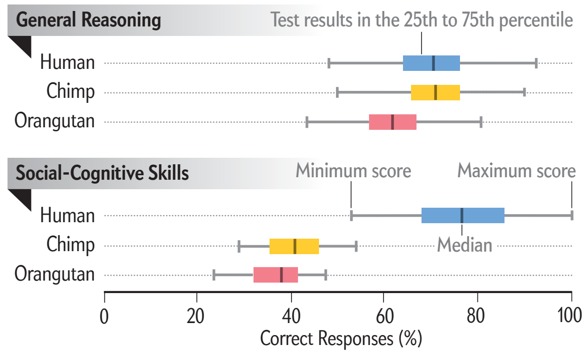
When Tomasello moved to a professorship at Emory University during the 1980s, he availed himself of the university's Yerkes primate research center to look for clues to this capacity in studies comparing the behaviors of children with those of chimps. The move set in motion a multidecade quest that he has continued at Max Planck since 1998.

In his studies of chimp learning, Tomasello noticed that apes do not ape each other the way humans imitate one another. One chimp might emulate another chimp using a stick to fetch ants out of a nest. Then others in the group might do the same. As Tomasello looked more closely, he surmised that chimps were able to understand that a stick could be used for "ant dipping," but they were unconcerned with mimicking one technique or another that might be used in hunting for the insects. More important, there was no attempt to go beyond the basics and then do some tinkering to make a new and improved ant catcher.

CROSS-SPECIES IQ TESTING

Smart as a Chimp?

One widely held hypothesis suggests that, overall, humans are more intelligent than other primates. A study by the Leipzig researchers showed that chimps and young children (though not orangutans) perform equally on tests of capacities measured by conventional IQ tests (*top*), such as spatial and quantitative abilities. But children do better on cognitive tests related to social skills, such as learning from others (*bottom*).



In human societies, in contrast, this type of innovation is a distinguishing characteristic that Tomasello calls a "ratchet effect." Humans modify their tools to make them better and then pass this knowledge along to their descendants, who make their own tweaks—and the improvements ratchet up. What starts as a lobbed stone projectile invented to kill a mammoth evolves over the millennia into a slingshot and then a catapult, a bullet, and finally an intercontinental ballistic missile.

This cultural ratchet provides a rough explanation for humans' success as a species but leads to another question: What specific mental processes were involved in transmitting such knowledge to others? The answer has to begin with speculations about changes in hominin physiology and behavior that may have taken place hundreds of thousands of years ago. One idea—the social brain hypothesis, put forward by anthropologist Robin Dunbar of the University of Oxford—holds that group size, and hence cultural complexity, scales up as brains get bigger. And scientists know that by 400,000 years ago, *Homo heidelbergensis,* probably our direct ancestor, had a brain almost as large as ours.

Tomasello postulates that, equipped with a bigger brain and confronted with the need to feed a growing population, early hominins began careful strategizing to track and outwit game. The circumstances exerted strong selection pressures for cooperation: any member of a hunting party who was not a team player—taking on a carefully defined role when tracking and cornering an animal—would have been excluded from future outings and so might face an unremittingly bleak future. If one hunter was a bad partner, Tomasello notes, the rest of the group would then decide: "We won't do this again." In his view, what separated modern humans from the hominin pack was an evolutionary adaptation for hypersociality.

The paleoarchaeological record of bones and artifacts is too scant to provide support for Tomasello's hypothesis. He draws

SOURCE: "HUMANS HAVE EVOLVED SPECIALIZED SKILLS OF SOCIAL COGNITION: THE CULTURAL INTELLIGENCE HYPOTHESIS," BY ESTHER HERRMANN ET AL., IN *SCIENCE*, VOL. 317; SEPTEMBER 7, 2007

his evidence from a comparison of child and chimp—matching our closest primate relative with a toddler who has yet to master a language or be exposed to formal schooling. The untutored child allows researchers to assess cognitive skills that have yet to be fully shaped by cultural influences and so can be considered to be innate.

Studies in Leipzig during the past decade or so have uncovered more similarities than differences between humans and chimps, but they also highlight what Tomasello calls "a small difference that made a big difference." One immense research undertaking, led by Esther Herrmann of the developmental and comparative psychology department at the Max Planck Institute under Tomasello's tutelage, ran from 2003 until its publication in *Science* in 2007. It entailed administering multiple cognitive tests to 106 chimpanzees at two African wildlife sanctuaries, 32 orangutans in Indonesia and 105 toddlers, aged two and a half years, in Leipzig.

The investigators set out to determine whether humans' bigger brain meant the children were smarter than great apes and, if so, what being smarter meant, exactly. The three species were tested on spatial reasoning (such as looking for a hidden reward), an ability to discriminate whether quantities were large or small, and an understanding of cause-and-effect relationships. It turned out that the toddlers and the chimpanzees scored almost identically on these tests (orangutans did not perform quite as well).

Humans have a special capacity for engaging in figurative "mind reading" of another person's thoughts. They use these deductions to make plans for achieving a joint goal—whether it be carrying a log or building a skyscraper.

When it came to social skills, though, there was no contest. Toddlers bested both chimps and orangutans on tests (adapted for nonverbal apes) that examined the ability to communicate, learn from others, and evaluate another being's perceptions and wishes. The researchers interpreted the results as showing that human children are not born with a higher IQ (general reasoning capacities) but rather come equipped with a special set of abilities—"cultural intelligence," as the *Science* study put it—that prepares them for learning later from parents, teachers and playmates. "It was really the first time that it was shown that social-cognitive abilities are the key skills that make us special in comparison to other animals," Herrmann says.

Digging deeper required probing for the specific psychological processes that underlie humans' ultrasocial tendencies. Tomasello's research showed that at about nine months of age, parent and child engage in a figurative form of mind reading. Each has what psychologists call a "theory of mind." Each is aware of what the other one knows when they look together at a ball or block and play a little game with it. Each carries a mental image of these items in the same way a group of *H. heidelbergensis* would have all visualized a deer intended as dinner. This capacity to engage with another person to play a game or achieve a common goal is what Tomasello calls shared intentionality (a term he borrowed from philosophy). In Tomasello's view, shared intentionality is an evolutionary adaptation unique to humans—a minute difference with momentous consequences, rooted in an inherited predisposition for a degree of cooperative social interactions that is absent in chimps or any other species.

THE BENEFITS OF MIND READING

THE INSTITUTE RESEARCHERS NOTED that chimps, too, can read one another's minds to some degree. But their natural inclination is to use whatever they learn in that way to outcompete one another in the quest for food or mates. The chimp mind, it appears, is involved in a kind of Machiavellian mental scheming—"If I do this, will he do that?"—as Tomasello explains it. "It is inconceivable," he said in an October 2010 talk at the University of Virginia, "that you would ever see two chimpanzees carrying a log together."

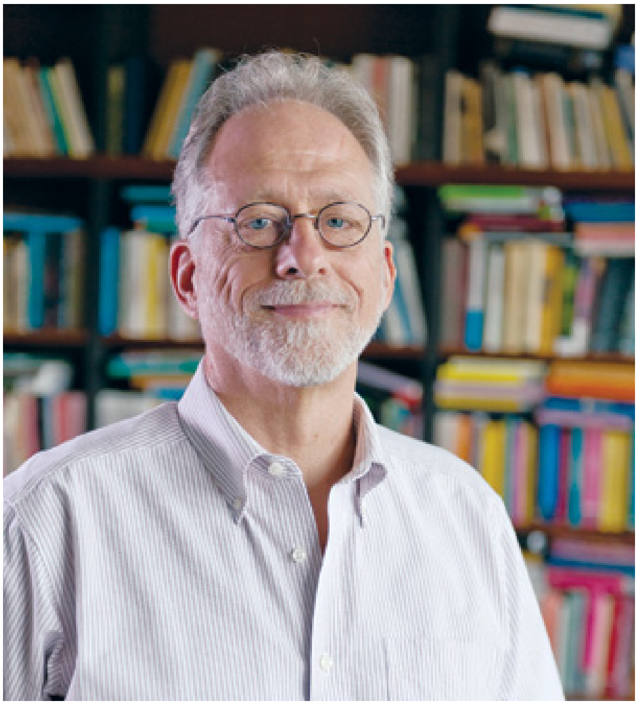
The Leipzig researchers formally demonstrated the differences that separate the two species in the rope-and-board experiment, in which two chimpanzees at the Leipzig Zoo could get a snack of fruit only if they both pulled a rope attached to a board. If food was placed at both ends of the board, the apes took the fruit closest to them. If the treats were placed in the middle, however, the more dominant ape would grab the food, and after a few trials, the subordinate simply stopped playing. In the institute's child lab, the children worked together, whether the gummy bears were placed in the middle or at the ends of the board. When the treat was in the middle, the three-year-olds negotiated so that each would get an equal share.

Ancestral humans' mutual understanding of what was needed to get the job done laid the basis for the beginnings of social interactions and a culture based on cooperation, Tomasello argues. This "common ground," as he calls it, in which members of a group know much of what others know, may have opened the way for development of new forms of communication.

An ability to devise and perceive shared goals—and to intuit immediately what a hunting partner was thinking—apparently allowed our hominin ancestors to make cognitive strides in other ways, such as developing more sophistication in communicative uses of gesturing than our ape relatives possess.

The basic gestural repertoire of our hominin kin may have once been similar to that of the great apes. Archaic humans may have pointed, as chimpanzees do today, to convey commands—"Give me this" or "Do that"—a form of communication centered on an individual's needs. Chimps, perhaps reminiscent of humans in a primeval past, still make no attempt to use these gestures for teaching or passing along information.

For humans, gesturing took on new meaning as their mental-processing abilities got better. A hunter would point to a glade in the forest to indicate where a deer was grazing, an ac-



MICHAEL TOMASELLO has pioneered studies comparing "a few small differences that make a large difference" in the cognitive abilities of humans relative to those of chimpanzees.

tion immediately understood by a nearby companion. The way such pointing can take on new meanings is evident in modern life. "If I point to indicate 'Let's go have a cup of coffee over there,' it's not in the language," Tomasello says. "The meaning of 'that café' is in the finger, not in the language."

Young children understand this type of pointing, but chimps do not. This difference became evident in one study in which the experimenter repeatedly put blocks on a plate that the child needed for building a tower, which the child then used. At a certain juncture, there were no objects left when needed, and so the infant started pointing to the now empty plate, indicating that she wanted one of the blocks that were no longer there. The child knew that the adult would make the correct inference—the ability to refer to an absent entity is, in fact, a defining characteristic of human language. At the zoo, chimps put through a similar exercise—with food substituted for blocks—did not lift a finger when facing a vacant plate.

Only slightly older children start to understand gestures that pantomime an action—moving a hand to one's mouth to represent hunger or thirst. Chimps seeing these gestures during a study remain clueless. An ape will understand what is happening when a human applies a hammer to a nut to get the meat but is befuddled when that same person makes a pounding motion on the hand to convey the idea of carrying out the same action.

This type of gesturing—an extension of humans' cognitive capacity for shared intentionality—may have been the basis for communicating abstract ideas needed to establish more elaborate social groups, whether they be a tribe or a nation. Pantomiming would have enabled people to create story lines, such as conveying "the antelope grazes on the other side of the hill" by holding both hands in a V pattern on the top of one's head to signify the animal and then raising and lowering the hands to depict the hill. These scenarios derive from comparative experiments demonstrating that toddlers have an intuitive understanding of iconic gestures for many familiar activities but that chimpanzees do not.

Some of this gesturing occurred perhaps not just through moving the hands but also through vocalizations intended to represent specific objects or actions. These guttural noises may have evolved into speech, further enhancing the ability to manage complex social relationships as populations continued to grow—and rivalries arose among tribal groups. A group adept at working together would outcompete those that bickered among themselves.

Humans' expanding cognitive powers may have promoted specific practices for hunting, fishing, plant gathering or marriage that turned into cultural conventions—the way "we" do things—that the group as a whole was expected to adopt. A collection of social norms required each individual to gain awareness of the values shared by the group—a "group-mindedness" in which every member conformed to an expected role. Social norms produced a set of moral principles that eventually laid a foundation for an institutional framework—governments, armies, legal and religious systems—to enforce the rules by which people live. The millennial journey that began with a particular mind-set needed by bands of hunters now scaled up to entire societies.

Chimps and other great apes never got started down this path. When chimps hunt together to prey on colobus monkeys in Ivory Coast, this activity, as Tomasello interprets it, entails every chimp trying to run down the monkey first to get the most meat, whereas human hunter-gatherers, even in contemporary settings, cooperate closely as they track game and later share the spoils equitably. Tomasello concludes that ape societies and those of other foragers such as lions may appear to cooperate, but the dynamics at play within the group are still fundamentally competitive in nature.

THE GREAT DEBATE

TOMASELLO'S VERSION of an evolutionary history is not universally accepted, even within the institution. One floor up from his office, in the department of primatology, Catherine Crockford talks me though a video her graduate student Liran Samuni made in March. It shows a young chimpanzee in the Taï National Park in Ivory Coast near the Liberian border.

The chimp the researchers call Shogun has just caught a large, black-and-white colobus monkey. Shogun is having trouble eating his still alive and squirming catch and issues a series of sharp "recruitment screams" to summon help from two elder hunters lodged in the tree canopy. Kuba, one of the two, arrives on the scene shortly, and Shogun calms down a bit and takes his first real bite. But then Shogun continues to scream until the other hunter, Ibrahim, shows up. The younger ape puts his finger in Ibrahim's mouth as a "reassurance gesture," a mannerism that ensures that all is well. Ibrahim gives the sought-for emotional support by not biting Shogun's finger. The three then share the meal. "It's interesting that he's recruiting these two dominant males that could take this whole monkey from him," Crockford says. "But as you can see, they're not taking it from him. He's still allowed to eat it."

COURTESY OF JACOBS FOUNDATION

Crockford argues that it is still too early to draw conclusions about the extent to which chimps cooperate. "I don't think we know the limits of what chimps are doing," she says. "I think [Tomasello's] arguments are brilliant and really clear in terms of our current knowledge, but I think that with new tools that we're taking to the field, we'll find out whether the current limits are the limits of what chimps can do or not." Crockford is working with several other researchers to develop tests that would identify the social-bonding hormone oxytocin in chimpanzee urine. Some studies have shown that the hormone rises when chimps share food, a sign that the animals may cooperate when feeding.

Crockford did her doctoral studies at the institute in Leipzig, with both Tomasello and Christophe Boesch, head of the Max Planck Institute's department of primatology. Boesch has argued against Tomasello's conclusions by highlighting his own extensive research in the Taï National Park showing that chimps have a highly collaborative social structure—one chimp steers the monkey prey in the desired direction; others block its path along the way or take on yet additional roles. Boesch's views on chimp cooperation are similar to those of Frans de Waal of the Yerkes National Primate Research Center at Emory [see "One for All," on page 68]. Still others criticize Tomasello from a diametrically opposing viewpoint. Daniel Povinelli of the University of Louisiana at Lafayette contends that Tomasello overstates chimps' cognitive capacities in suggesting that they have some ability to understand the psychological state of others in the group.

For his part, Tomasello seems to enjoy being in the midst of this academic jousting, saying: "In my mind, Boesch and de Waal are anthropomorphizing apes, and Povinelli is treating them like rats, and they're neither." He adds, jokingly, "We're in the middle. Since we're getting attacked equally from both sides, we must be right."

Condemnation from some quarters is tempered by a deep respect from others. "I used to think that humans were very similar to chimps," says Jonathan Haidt, a leading social scientist at the New York University Stern School of Business. "Over the years, thanks in large part to Tomasello's work, I've come to believe that the small difference he has studied and publicized—the uniquely human ability to do shared intentionality—took us over the river to a new shore, where social life is radically different."

Resolving these debates will require more research from zoo, lab and field station—perhaps through new studies on the extent to which chimps have a theory of mind about others. Still other research already under way by Tomasello's group is intended to determine whether the conclusions about human behavior, drawn from tests on German children, carry over if similar tests are performed on children in Africa or Asia. One study asks whether German preschoolers share their collective sense of what is right or wrong with the Samburu, a seminomadic people in northern Kenya.

There may also be room to look more deeply at human-ape differences. One of Tomasello's close longtime colleagues, Josep Call, who heads the Wolfgang Köhler Center, thinks that shared intentionality alone may not suffice to explain what makes humans special. Other cognitive capacities, he says, may also differentiate humans from other primates—one example may be "mental time travel"—our ability to imagine what may happen in the future.

Advancing an interspecies research agenda beyond comparisons of human and ape psychology may involve looking at differences in genetic makeup among chimps, humans—and even our closest evolutionary kin, the Neandertals.

More perspective on the overlap between humans and chimps may come from looking inside the human brain—an endeavor that is ongoing on yet another floor at Max Planck. Svante Pääbo, who led a team that finished an initial sequencing of the Neandertal genome in 2010, conjectures in a recent book that Tomasello's ideas about the uniqueness of human thinking may ultimately be tested through genetic analyses.

When those studies begin, a logical place to start would be to fuse research on chimp and human behaviors with the quixotic journey to understand the interactions among the hundreds of genes involved in autism. Children with the disorder, not unlike chimps, have difficulty understanding social cues. Comparing the genes in children with autism with those in unaffected children—and then with the DNA of chimps and perhaps even Neandertals, our closest evolutionary cousins—may yield a better understanding of a genetic basis for human sociality.

These investigations may also help explain why, over millennia, we progressed from bands of foragers to societies that not only provide food and shelter more efficiently than chimps do but also offer unceasing opportunities for social dealings—chances to move to any corner of the planet within a day's time or to convey messages to Tucson or Timbuktu as fast as a thought comes to mind. SA

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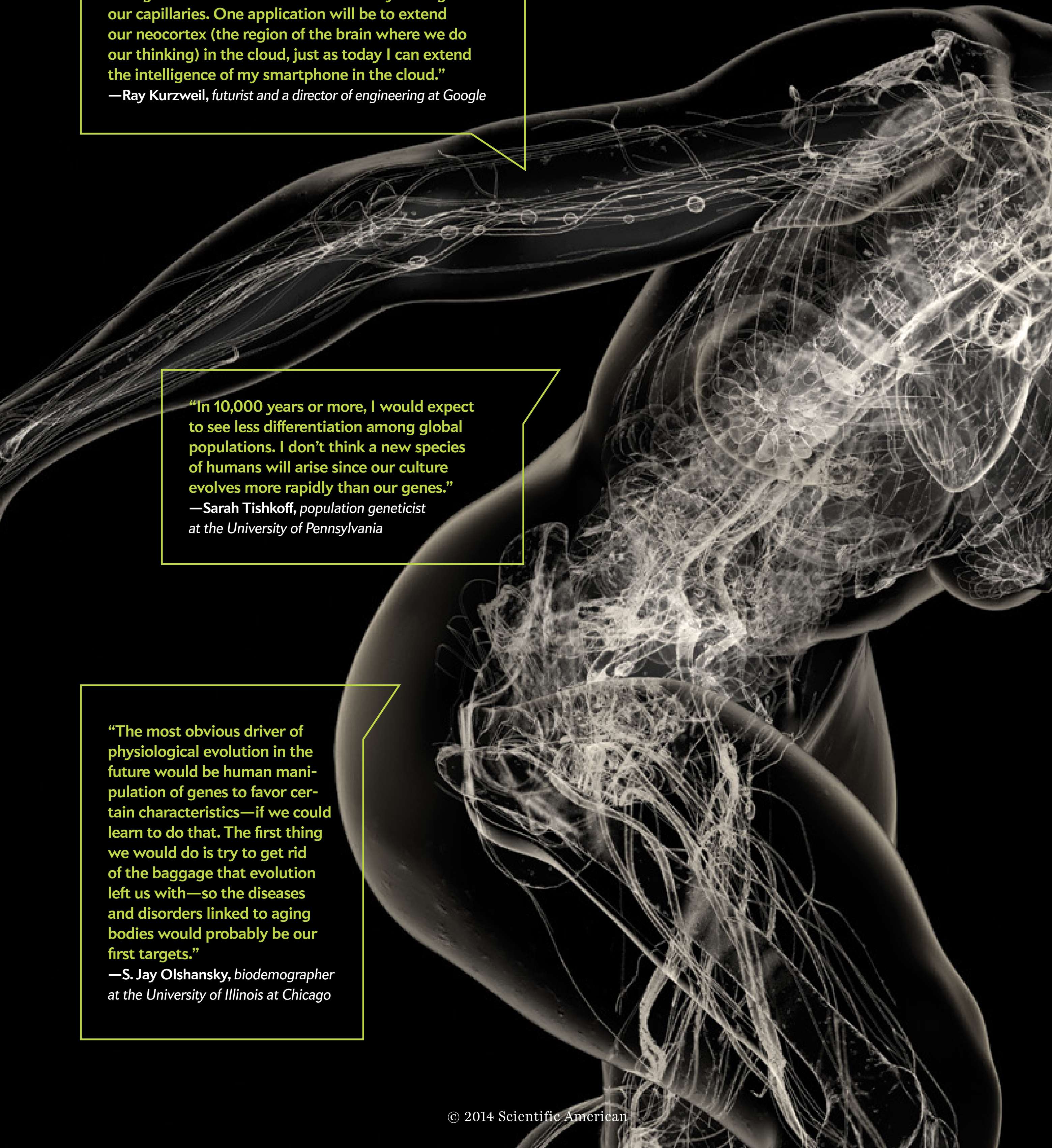

"Parkinson's patients and the deaf already can have computerized devices implanted. By the 2030s this will become ubiquitous. Computers will be small enough to enter our brains noninvasively through our capillaries. One application will be to extend our neocortex (the region of the brain where we do our thinking) in the cloud, just as today I can extend the intelligence of my smartphone in the cloud."
—Ray Kurzweil, *futurist and a director of engineering at Google*

"In 10,000 years or more, I would expect to see less differentiation among global populations. I don't think a new species of humans will arise since our culture evolves more rapidly than our genes."
—Sarah Tishkoff, *population geneticist at the University of Pennsylvania*

"The most obvious driver of physiological evolution in the future would be human manipulation of genes to favor certain characteristics—if we could learn to do that. The first thing we would do is try to get rid of the baggage that evolution left us with—so the diseases and disorders linked to aging bodies would probably be our first targets."
—S. Jay Olshansky, *biodemographer at the University of Illinois at Chicago*

3

WHERE WE ARE GOING

WE ASKED leading scientists how they think humans will evolve in the future. Here is what they had to say. For more expert commentary, go to **ScientificAmerican.com/sep2014/predictions**

"Evolution is incessant, and humans, like every other life-form on earth, are evolving and will continue to evolve; however, nobody knows what humans will become other than maybe going extinct. Evolution has its own ways that no one can predict for sure."
—**Yohannes Haile-Selassie,** *paleoanthropologist at the Cleveland Museum of Natural History*

Illustration by Bryan Christie, Reporting by Kevin Schultz


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THE NETWORKED PRIMATE

For the first time in the history of our species, we are never alone and never bored. Have we lost something fundamental about being human?

Interview by Mark Fischetti

ERIK JACOBS Redux Pictures (Turkle)

IN BRIEF

WHO
SHERRY TURKLE

VOCATION
Sociologist

WHERE
Massachusetts Institute of Technology

RESEARCH FOCUS
How people interact with technology and how that affects human relationships.

BIG PICTURE
Social networking is making us less social.

Chances are that you have a smartphone, a Facebook page and a Twitter account and that you have found yourself ignoring a friend or family member who is in the same room as you because you are totally engrossed in your social technology. That technology means never having to feel alone or bored. Yet ironically, it can make us less attentive to the people closest to us and even make it hard for us to simply be with ourselves.

Many of us are afraid to make this admission. "We're still in a romance with these technologies," says Sherry Turkle of the Massachusetts Institute of Technology. "We're like young lovers who are afraid that talking about it will spoil it."

Turkle has interviewed, at length, hundreds of individuals of all ages about their interactions with smartphones, tablets, social media, avatars and robots. Unlike previous disruptive innovations such as the printing press or television, the latest "always on, always on you" technology, she says, threatens to undermine some basic human strengths that we need to thrive. In the conversation that follows, which has been edited for space, Turkle explains her concerns, as well as her cautious optimism that the youngest among us could actually resolve the challenges.

Illustration by Martin O'Neill

SCIENTIFIC AMERICAN: What concerns you most about our constant interaction with our social technologies?

TURKLE: One primary change I see is that people have a tremendous lack of tolerance for being alone. I do some of my fieldwork at stop signs, at checkout lines at supermarkets. Give people even a second, and they're doing something with their phone. Every bit of research says people's capacity to be alone is disappearing. What can happen is that you lose that moment to have a daydream or to cast an eye inward. Instead you look to the outside.

Is that an issue for individuals of all ages?

Yes, but children especially need solitude. Solitude is the precondition for having a conversation with yourself. This capacity to be with yourself and discover yourself is the bedrock of development. But now, from the youngest age—even two, or three, or four—children are given technology that removes solitude by giving them something externally distracting. That makes it harder, ironically, to form true relationships.

Maybe people just don't want to be bored.

People talk about never needing to have a lull. As soon as it occurs, they look at the phone; they get anxious. They haven't learned to have conversations or relationships, which involve lulls.

Are we valuing relationships less, then?

People start to view other people in part as objects. Imagine two people on a date. "Hey, I have an idea. Instead of our just looking at each other face-to-face, why don't we each wear Google Glass, so if things get a little dull, I can just catch up on my e-mail? And you won't know." This disrupts the family, too. When Boring Auntie starts to talk at the family dinner table, her little niece pulls out her phone and goes on Facebook. All of a sudden her world is populated with snowball fights and ballerinas. And dinner is destroyed. Dinner used to be the utopian ideal of the American family having a canonical three-generation gathering. Facebook is what's utopian now.

What about people who take their phones to bed? They're asleep, so why would they feel alone?

I have interviewed enough middle school and high school kids: "So tell me, do you answer your texts in the middle of the night?" "Oh, yeah." I call it "I share, therefore I am," as a style of being.

If you're sharing in the middle of the night and responsive to people in the middle of the night, you're in a different zone. And all these people feel responsible to respond. The expectation is constant access. Everyone is ready to call in the advice and the consent of their peers. I'm doing a case study of a young woman who has 2,000 followers on Instagram. She'll ask about a problem at 9:00 at night, and at 2:00 in the morning she's getting responses, and she's awake to get those responses. This is 2:00 in the morning for a lot of kids.

Where does this lead for someone who lives that way?

If you don't call a halt to it, I think you don't fully develop a sense of an autonomous self. You're not able to be in personal relationships, business relationships, because you don't feel fully competent to handle major things on your own. You run into trouble if you're putting everything up, ultimately, for a vote.

You're crowdsourcing your life.

You're crowdsourcing major decisions. I hope it's likely, however, that a person reaches a point where they're on a job—they're not twentysomething, they're thirtysomething—and this starts to become less comfortable, and they develop emotional skills that they really haven't worked on.

What about our interactions with automated personalities and robots?

When we started looking at this in the 1970s, people took the position that even if simulated thinking might be thinking, simulated feeling was not feeling. Simulated love was never love. But that's gone away. People tell me that if Siri [the iPhone voice] could fool them a little better, they'd be happy to talk to Siri.

Isn't that like the movie *Her?*

Absolutely. The current position seems to be that if there's a robot that could fool me into thinking that it understands me, I'm good to have it as a companion. This is a significant evolution in what we ask for in our interactions, even on intimate matters. I see it in kids. I see it in grown-ups. The new robots are designed to make you feel as though you're understood. Yet nobody is pretending that any of them understands anything.

What line does that cross—that there's no empathy?

There's no authentic exchange. You're saying empathy is not important to the feeling of being understood. And yet I interviewed a woman who said to me that she's okay with a robot boyfriend. She wants one of these sophisticated Japanese robots. I looked at her and said, "You know that it doesn't understand you." She said, "Look, I just want civility in the house. I just want something that will make me feel not alone."

People are also good with a robot that could stand in as a companion for an older person. But I take a moral position here because older people deserve to tell the story of their life to someone who understands what a life is. They've lost spouses; they've lost children. We're suggesting they tell the story of their life to something that has no idea what a life is or what a loss is.

It's crucial to understand that this changing interaction is not just a story about technology. It's a story about how we are evolving when we're faced with something passive. I hope we're going to look closer at people's willingness to project humanity onto a robot and to accept a facade of empathy as the real thing, because I think such interactions are a dead end. We want more from technology and less from each other? Really?

Do avatars and virtual reality present the same issues?

In these cases, we are moving from life to the mix of your real life and your virtual life. One young man put it very succinctly: "Real life is just one window, and it's not necessarily my best one." People forgot about virtual reality for a while, but now the acquisition of Oculus by Facebook raises it again—Mark Zuckerberg's fantasy that you will meet up with your friends in a virtual world where

SCIENTIFIC AMERICAN ONLINE Turkle questions the effects of using mobile technology to document our lives at ScientificAmerican.com/sep2014/turkle

everybody looks like Angelina Jolie and Brad Pitt, you live in a beautiful home, and you present only what you want to present. We're evolving toward thinking of that as a utopian image.

But skeptics say your avatar is not different from the real you.
Well, we do perform all the time. I'm trying to do my best Sherry Turkle right now. But it's a little different from me hanging out in my pajamas. What's different with an avatar or on Facebook is that you get to edit. A woman posts a photo of herself and then works on the color and background and lighting. Why? Because she wants it a certain way. We've never before been able to have it the way we wanted it. And now we can. People love that.

I asked an 18-year-old man, "What's wrong with conversation?" He said, "It takes place in real time. You can't control what you're going to say." It was profound. That's also why a lot of people like to do their dealings on e-mail—it's not just the time shifting; it's that you basically can get it right.

One reason for the rise of humans is that functioning in groups gives each member a better chance to succeed. Will the move toward living online undermine those benefits?
Oh, this is the question before us. Are we undermining or are we enhancing our competitive advantage? A lot of my colleagues would say we're enhancing it. The Internet is giving us new ways of getting together, forming alliances. But I think we are at a point of inflection. While we were infatuated with the virtual, we dropped the ball on where we actually live. We need to balance how compelling the virtual is with the realities that we live in our bodies and on this planet. It is so easy for us to look the other way. Are we going to get out there and make our real communities what they should be?

Your critics say there's nothing to worry about because this "new technology" situation is not really new. We went through this with television—you know, TV is there to watch your kids so you don't have to.
First of all, television can be a group exercise. I grew up in a family that sat around a TV and watched it together, fought about what was on the TV together, commented on it together. But when everybody watches their own show in their own room, so to speak, that stops. Technology that is always on and always on you—that is a quantum leap. I agree that there have been quantum leaps before: the book. The difference with "always on," however, is that I really don't have a choice.

You mean, you could turn off the TV and still function.
I cannot live my professional life or my personal life without my phone or my e-mail. My students can't even obtain their syllabus without it. We don't have an opt-out option from a world with this technology. The question is, How are we going to live a more meaningful life with something that is always on and always on you? And wait until it's in your ear, in your jacket, in your glasses.

So how do we resolve that?
It's going to develop as some sort of common practice. I think companies will get involved, realizing that it actually isn't good for people to be constantly connected. Our etiquette will get involved; today if I get a message and don't get back to people in 24 hours, they're worried about me, or they're mad that I haven't replied. Why? I think we will change our expectation of having constant access.

Any suggestions for how we can get started?
One argument I make is that there should be sacred spaces: the family dinner table, the car. Make these the places for conversation because conversation is the antidote to a lot of the issues I'm describing. If you're talking to your kids, if you're talking to your family, if you're talking to a community, these negative effects don't arise as much.

And we should be talking more about the technologies?
My message is not antitechnology. It's pro conversation and pro the human spirit. It's really about calling into questions our dominant culture of more, better, faster. We need to assert what we need for our own thinking, for our own development, and for our relationships with our children, with our communities, with our intimate partners. As for the robots, I'm hoping that people will realize that what we're really disappointed in is ourselves. It's so upsetting to me. We're basically saying that we're not offering one another the conversation and the companionship. That, really, is the justification for talking to a robot that you know doesn't understand a word you're saying. We are letting each other down. It's not about the robots. It's about us.

So who is going to stop this train we are on?
The most optimistic thing I see is the young people who've grown up with this technology but aren't smitten by it, who are willing to say, "Hold on a second." They see the ways in which it's undermined life at school and life with their parents. This is where I'm guardedly hopeful.

I have so many examples of children who will be talking with their parents; something will come up, and the parent will go online to search, and the kid will say, "Daddy, stop Googling. I just want to talk to you." When I go to the city park, I see kids go to the top of the jungle gym and call out, "Mommy, Mommy!" and they're being ignored. They object to being ignored when they're five, eight or nine. But when I interview these kids when they're 13, 14 or 15, they become reflective. They say, "I'm not going to bring up my children the way I'm being brought up." They're going to have rules, like no phones at dinner.

I also see evidence that dealing with some of this technology is feeling to them like work—the whole notion that you have to constantly keep up your Facebook profile. So I think there's every possibility that the children will lead us. They see the costs. They think, "I don't have to give up this technology, but maybe I could be a little smarter about it." SA

Mark Fischetti is a senior editor at Scientific American.

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scientificamerican.com/magazine/sa

STILL EVOLVING (AFTER ALL THESE YEARS)

For 30,000 years our species has been changing remarkably quickly. And we're not done yet

By John Hawks

IN BRIEF

Some scientists and science communicators have claimed that humans are no longer subject to natural selection and that human evolution has effectively ceased.

In fact, humans have evolved rapidly and remarkably in the past 30,000 years. Straight, black hair, blue eyes and lactose tolerance are all examples of relatively recent traits.

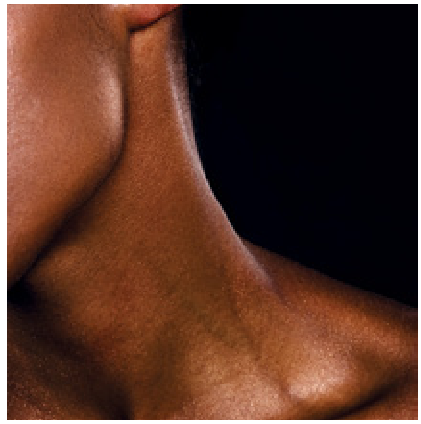
Such rapid evolution has been possible for several reasons, including the switch from hunting and gathering to agrarian-based societies, which permitted human populations to grow much larger than before. The more people reproduce within a population, the higher the chance of new advantageous mutations.

Humans will undoubtedly continue to evolve into the future. Although it may seem that we are headed toward a cosmopolitan blend of human genes, future generations will likely be striking mosaics of our entire evolutionary past.

Illustration by Christian Northeast

John Hawks is an anthropologist and an expert on human evolution at the University of Wisconsin–Madison.

HUMANS ARE WILLFUL CREATURES. No other species on the planet has gained so much mastery over its own fate. We have neutralized countless threats that once killed us in the millions: we have learned to protect ourselves from the elements and predators in the wild; we have developed cures and treatments for many deadly diseases; we have transformed the small gardens of our agrarian ancestors into the vast fields of industrial agriculture; and we have dramatically increased our chances of bearing healthy children despite all the usual difficulties.



Many people argue that our technological advancement—our ability to defy and control nature—has made humans exempt from natural selection and that human evolution has effectively ceased. There is no "survival of the fittest," the argument goes, if just about everyone survives into old age. This notion is more than just a stray thought in the public consciousness. Professional scientists such as Steven Jones of University College London and respected science communicators such as David Attenborough have also declared that human evolution is over.

But it is not. We have evolved in our recent past, and we will continue to do so as long as we are around. If we take the more than seven million years since humans split from our last common ancestor with chimpanzees and convert it to a 24-hour day, the past 30,000 years would take about a mere six minutes. Yet much has unfolded during this last chapter of our evolution: vast migrations into new environments, dramatic changes in diet and a more than 1,000-fold increase in global population. All those new people added many unique mutations to the total population. The result was a pulse of rapid natural selection. Human evolution is not stopping. If anything, it is accelerating.

AN ANTHROPOLOGICAL LEGACY

SKELETONS OF ANCIENT PEOPLE have long suggested that humans evolved certain traits swiftly and recently. About 11,000 years ago, as people started to transition from hunting and gathering to farming and cooking, human anatomy changed. Ten thousand years ago, for example, people's teeth averaged more than 10 percent larger in Europe, Asia and North Africa than today. When our ancestors started to eat softer cooked foods that required less chewing, their teeth and jaws shrank, bit by bit, each generation.

Although anthropologists have known about such traits for decades, only in the past 10 years has it become clear just how new they really are. Studies of human genomes have made the recent targets of selection highly visible to us. It turns out, for example, that descendants of farmers are much more likely to have a greater production of salivary amylase, a key enzyme that breaks down starches in food. Most people alive today have several copies of the gene that codes for amylase, *AMY1*. Modern hunter-gatherers—such as the Datooga in Tanzania—tend to have far fewer copies than people whose ancestors came from farming populations, whether they live in Africa, Asia or the Americas. Getting a jump on starch processing at the point of entry seems to have been an advantage for ancient farmers wherever they adopted starchy grains.

Another dietary adaptation is one of the best-studied examples of recent human evolution: lactose tolerance. Nearly everyone in the world is born with the ability to produce the enzyme lactase, which breaks down the milk sugar lactose and makes it easier to extract energy from milk—essential for the survival of a suckling child. Most people lose this ability by adulthood. At least five different times in our recent evolutionary past, as people started to discover dairy, a genetic mutation arose to lengthen the activity of the lactase gene. Three of the mutations originated in different parts of sub-Saharan Africa, where there is a long history of cattle herding. Another one of the five genetic tweaks is common in Arabia and seems to have sprung up in ancient populations of camel and goat herders.

The fifth and most common variant of the mutation that keeps the lactase gene turned on in adulthood is found today in human populations stretching from Ireland to India, with its highest frequencies across northern Europe. The mutation originated in a single individual 7,500 years ago (give or take a few

JOSEPH CLARK *Getty Images*

MANY COMMONPLACE FEATURES of human biology are relatively new. Blue eyes, straight, thick black hair, the ability to digest milk in adulthood and some mutations that lightened skin all emerged in the past 30,000 years.

ANTHONY LEE *Getty Images* (eye); ANDREAS KUEHN *Getty Images* (hair); DAITOZEN *Getty Images* (milk)

thousand years). In 2011 scientists analyzed DNA recovered from Ötzi the Iceman, who was naturally mummified about 5,500 years ago in northern Italy. He did not have the lactose-tolerance mutation, a hint that it had not yet become common in this region thousands of years after its initial origin. In following years, researchers sequenced DNA extracted from the skeletons of farmers who lived in Europe more than 5,000 years ago. None carried the lactase mutation. Yet in the same region today, the lactase-persistence mutation occurs in hundreds of millions of people—more than 75 percent of the gene pool. This is not a paradox but the mathematical expectation of natural selection. A new mutation under selection grows exponentially, taking many generations to become common enough to notice in a population. But once it becomes common, its continued growth is very rapid and ultimately dominates.

THE SHALLOWNESS OF RACES

WHAT IS PERHAPS MOST EXTRAORDINARY about our recent evolution is how many common physical features are completely new to human anatomy. The thick, straight black hair shared by most East Asians, for example, arose only within the past 30,000 years, thanks to a mutation in a gene called *EDAR,* which is crucial for orchestrating the early development of skin, hair, teeth and nails. That genetic variant traveled with early colonizers of the Americas, all of whom share an evolutionary past with East Asians.

In fact, the overall evolutionary history of human skin, hair and eye pigmentation is surprisingly shallow. In the earliest stages of our evolution, all our ancestors had dark skin, hair and eyes. Since this initial state, dozens of genetic changes have lightened these features to some extent. A few of these changes are ancient variations present within Africa but more common elsewhere in the world. Most are new mutations that have emerged in one population or another: a change in a gene named *TYRP1,* for instance, that makes certain Solomon Islanders blond; the *HERC2* mutation that results in blue eyes; changes to *MC1R* that causes red hairs to sprout instead of black ones; and a mutation in the *SLC24A5* gene that lightens skin color and that is now found in up to 95 percent of Europeans. As in the case of lactase, ancient DNA is giving clear information about the antiquity of such mutations. Blue eyes seem to have appeared in people who lived more than 9,000 years ago, but the massive change to *SLC24A5* is not found in the DNA of ancient skeletons from the same time period. Skin, hair and eye color evolved with stunning speed.

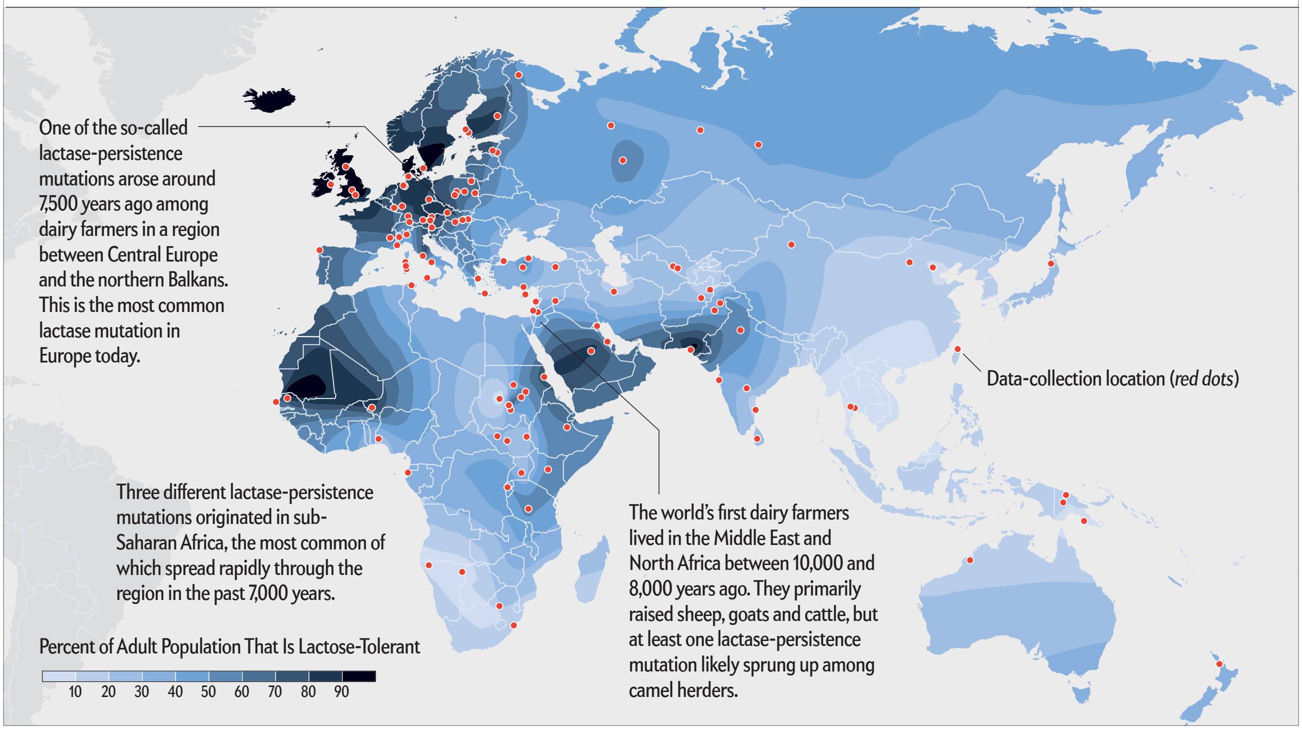
Variations in pigmentation are some of the most obvious differences between the races and, in some ways, the easiest to study. Scientists have also investigated much odder and less evident features of human anatomy. Consider the variations of earwax. Most people in the world today have sticky earwax. In contrast, many East Asians have dry, flaky earwax that does not stick together. Anthropologists have known about this variation for more than 100 years, but geneticists did not uncover the cause until recently. Dry earwax results from a relatively new mutation to a gene called *ABCC11.* Only 30,000 to 20,000 years old, the mutation also affects the apocrine glands, which produce sweat. If you have stinky armpits and sticky earwax, chances are you have the original version of *ABCC11.* If you have dry earwax and a little less need for deodorant, you probably have the newer mutation.

A few thousand years before dry earwax first appeared among East Asians, another seemingly simple mutation started saving millions of Africans from a deadly disease. A gene called *DARC* produces a starchy molecule on the surface of red blood cells that mops up excess immune system molecules known as chemokines from the blood. About 45,000 years ago a mutation

FINDINGS

The Milk Mutation

Enjoying dairy in adulthood is a privilege that emerged relatively recently in our evolutionary history. We depend on the enzyme lactase to break down lactose, the sugar found in milk, but the human body usually stops producing lactase after adolescence. In fact, most of the world's adults are lactose-intolerant. Within the past 10,000 years, however, different populations of dairy farmers independently evolved genetic mutations that kept lactase active throughout life. Scientists have identified five such mutations, but there are likely several more. Collectively, all these adaptations explain the prevalence of lactose tolerance seen around the world today.



SOURCE: GLOBAL LACTASE PERSISTENCE ASSOCIATION DATABASE

Map by XNR Productions

in *DARC* conferred remarkable resistance to *Plasmodium vivax,* one of the two most prevalent malaria parasites infecting humans today. The *vivax* parasites enter red blood cells through the DARC molecule encoded by the gene, so hindering the expression of *DARC* keeps the pathogens at bay. The absence of *DARC* also increased the amount of inflammation-causing chemokines circulating in the blood, which has in turn been linked to an increase in prostate cancer rates in African-American men. Yet on the whole, the mutation was so successful that 95 percent of people living below the Sahara now have it, whereas only 5 percent of Europeans and Asians do.

THE POWER OF RANDOM

WE ARE USED TO THINKING about evolution as a process of "good" genes replacing "bad" ones, but the most recent phase of human adaptation is a testament to the power of randomness in evolution. Beneficial mutations do not automatically persist. It all depends on timing and population size.

I first learned this lesson from the late anthropologist Frank Livingstone. The beginning of my training coincided with the end of his long career, during which he investigated the genetic basis for malaria resistance. More than 3,000 years ago in Africa and India, a mutation arose in the gene coding the oxygen-transporting blood cell molecule known as hemoglobin. When people inherited two copies of this mutation—dubbed hemoglobin S—they developed sickle cell anemia, a disease in which unusually shaped blood cells clog vessels. Red cells are normally supple and flexible enough to squeeze through tiny capillaries, but the mutant blood cells were rigid and pointed into the characteristic "sickle" shape. As it turns out, changing the shape of red blood cells also thwarted the ability of the malaria parasite to infect those cells.

Another mutation that interested Livingstone was hemoglobin E. Common in Southeast Asia today, hemoglobin E confers substantial malaria resistance without the severe side effects of hemoglobin S. "Hemoglobin E seems like it would be a lot better to have than hemoglobin S," I said in class one day. "Why didn't they get E in Africa?"

"It didn't happen there," Livingstone said.

His reply stunned me. I had supposed natural selection to be the most powerful force in evolution's arsenal. Humans had lived with deadly *falciparum* malaria for thousands of years in Africa. Surely natural selection would have weeded out less helpful mutations and hit on the most successful one.

Livingstone went on to show how the previous existence of hemoglobin S in a population made it harder for hemoglobin E

SCIENTIFIC AMERICAN ONLINE To learn about how humans recently adapted to high altitudes, go to ScientificAmerican.com/sep2014/hawks-origins

to invade. Malaria rips through a population full of only normal hemoglobin carriers, and a new mutation that provides a slight advantage can quickly become more common. Yet a population already supplied with the protective hemoglobin S mutation will have a lower mortality risk. Sickle cell carriers still face formidable risks, but hemoglobin E is less of a *relative* advantage in a population that already has this imperfect form of malaria resistance. Perversely, what matters is not only the luck of having the mutation but also *when* the mutation happens. A partial adaptation with bad side effects can win, at least over the few thousand years humans have been adapting to malaria.

Instead of a featureless mass of café-au-lait-colored clones, we are already starting to see a glorious riot of variations—dark-skinned, freckled blondes and striking combinations of green eyes and olive skin.

Ever since humans first began battling malaria, scores of different genetic changes emerged that increased immunity to the disease, different ones in different places. Each started as a serendipitous mutation that managed to persist in a local population despite being very rare at first. Any one of those mutations was, individually, unlikely to last long enough to become established, but the huge and rapidly increasing population size of our ancestors gave them many more rolls of the dice. As human populations have spread into new parts of the world and grown larger, they have rapidly adapted to their new homes precisely because those populations were so big.

OUR EVOLUTIONARY FUTURE

HUMAN POPULATIONS CONTINUE to evolve today. Unlike the distant past, where we must infer the action of selection from its long-term effects on genes, today scientists can watch human evolution in action, often by studying trends in health and reproduction. Even as medical technology, sanitation and vaccines have greatly extended life spans, birth rates in many populations still vacillate.

In sub-Saharan Africa, women who have a certain variant of a gene called *FLT1* and who are pregnant in the malarial season are slightly more likely to bear children than are pregnant women who lack the variant, because the possessors have a lower risk that the placenta will be infected by malaria parasites. We do not yet understand how this gene reduces the risk of placental malaria, but the effect is profound and measurable.

Stephen Stearns of Yale University and his colleagues have examined years of records from long-term public health studies to see which traits may correlate with reproduction rates today. During the past 60 years, relatively short and heavy women in the U.S. who have low cholesterol counts had slightly more children on average than women who have the opposite traits. Why these traits have been related to family size is not yet clear.

New public health studies on the horizon, such as U.K. Biobank, will be tracking the genotypes and lifetime health of hundreds of thousands of people. Such studies are being undertaken because the interactions of genes are complicated, and we need to examine thousands of outcomes to understand which genetic changes underlie human health. Tracing the ancestry of human mutations gives us a tremendous power to observe evolution over hundreds of generations but can obscure the complex interactions of environment, survival and fertility that unfolded in the past. We see the long-term winners, such as lactase persistence, but may miss the short-term dynamics. Human populations are about to become the most intensively observed long-term experiment in evolutionary biology.

What will the future of human evolution look like? Across the past few thousand years, human evolution has taken a distinctive path in different populations yet has maintained surprising commonality. New adaptive mutations may have elbowed their way into human populations, but they have not muscled out the old versions of genes. Instead the old, "ancestral" versions of genes mostly have remained with us. Meanwhile millions of people are moving between nations every year, leading to an unprecedented rate of genetic exchanges and mixture.

With such a high rate of genetic mixing, it may seem reasonable to expect that additive traits—for example, pigmentation, where many different genes have independent effects on skin color—will become ever more blended in future human populations. Could we be looking at a human future where we are a homogeneous slurry instead of a colorful stew of variability?

The answer is no. Many of the traits that differ between human populations are not additive. Even pigmentation is hardly so simple, as is readily seen in mixed populations in the U.S., Mexico and Brazil. Instead of a featureless mass of café-au-lait-colored clones, we are already starting to see a glorious riot of variations—dark-skinned, freckled blondes and striking combinations of green eyes and olive skin. Each of our descendants will be a living mosaic of human history. SA

MORE TO EXPLORE

Are Human Beings Still Evolving? It Would Seem That Evolution Is Impossible Now That the Ability to Reproduce Is Essentially Universally Available. Are We Nevertheless Changing as a Species? Meredith F. Small; Ask the Experts, ScientificAmerican.com, October 21, 1999.

African Adaptation to Digesting Milk Is "Strongest Signal of Selection Ever." Nikhil Swaminathan; ScientificAmerican.com, December 11, 2006.

Did Lactose Tolerance First Evolve in Central, Rather Than Northern Europe? Lynne Peeples; ScientificAmerican.com, August 28, 2009.

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The Future of Human Evolution. John Rennie; From the Editors, March 2001.

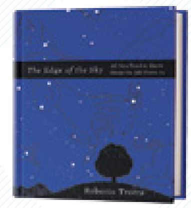
scientificamerican.com/magazine/sa

MORE TO EXPLORE For more recommendations and a slide show of comics from *What If?* author Munroe, go to **ScientificAmerican.com/sep2014/recommended**

COLLIDING Antennae galaxies, or "Star-Crowds"

The Edge of the Sky: All You Need to Know about the All-There-Is

by Roberto Trotta. Basic Books, 2014 ($16.99)



Some of the most fundamental concepts in science can also be the most impenetrable. In an effort to make the study of the universe's origins accessible, cosmologist Trotta challenged himself to explain it using only the 1,000 most common words in English. That leaves out words such as "galaxy" (which he calls "Star-Crowd") and "universe" ("the All-There-Is"). For example, on Edwin Hubble wondering if the fuzzy blobs in the night sky that turned out to be galaxies actually lay beyond the Milky Way, he writes, "If he could answer the question of how far away the White Shadows were, he reasoned, he would find out whether they were part of our own Star-Crowd. And if they weren't, this would show that the All-There-Is was much bigger than anyone thought." The result is a surprisingly clear, and often poetic, primer on such complicated topics as the big bang, dark energy and the possibility of multiverses.

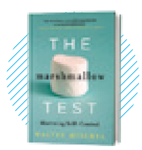
What If? Serious Scientific Answers to Absurd Hypothetical Questions

by Randall Munroe. Houghton Mifflin Harcourt, 2014 ($24)

Former NASA roboticist Munroe has gained a cult following for his witty science-themed Web comic *xkcd*. Here, with drawings, math and logical reasoning, he answers strange and intriguing questions submitted by online readers, such as "If someone's DNA suddenly vanished, how long would that person last?" and "How many Lego bricks would it take to build a bridge capable of carrying traffic from London to New York?" The answers are often surprising—for example, you could buy all the property in London and ship it, piece by piece, to New York for less than the cost of such a bridge, Munroe calculates. Some questions deemed too "weird" to answer still get amusing comic responses, such as "Could you survive a tidal wave by submerging yourself in an in-ground pool?" and "What if I swallow a tick that has Lyme disease?"

The Marshmallow Test: Mastering Self-Control

by Walter Mischel. Little, Brown, 2014 ($29)



One marshmallow now or two later? This simple choice has agonized preschoolers since the 1960s, when psychologist Mischel began running his famous experiment to test children's ability to delay gratification. It turns out that a kid's performance on this willpower test predicts far-reaching outcomes such as SAT scores, relationship satisfaction and even body-mass index later in life. The good news is that the ability to resist instant gratification for longer-term rewards is not innate but can be learned. "It is a skill open to modification, and it can be enhanced through specific cognitive strategies that have now been identified," Mischel writes in this account of the history of the test and the revelations it has produced. Admittedly impatient himself, he details the tactics that help our minds resist temptation and the implications of his work on child rearing, education and public policy.

Shocked: Adventures in Bringing Back the Recently Dead

by David Casarett. Current, 2014 ($27.95)

"Although the science that makes resuscitation possible is amazing, its costs—financial, ethical, and emotional—can be enormous," writes Casarett, a hospice physician. His book tells stories of miraculous returns from the brink of death, as well as sadder tales of people "saved" from dying only to linger on in a brain-dead limbo that arguably brought worse pain to the patients and their families. Casarett offers no easy answers, but many compelling questions, in this investigation of the history and possible future of resuscitation, suspended animation, cryogenic preservation and other death-defying procedures. "Maybe if someone can't be revived quickly and easily, we should leave well enough alone?" he writes. "Most of all, I wonder how this technology is going to change the way that we die."

HUBBLE LEGACY ARCHIVE/NASA/ESA

Viewing the world with a rational eye

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His next book is *The Moral Arc.* Follow him on Twitter @michaelshermer

Surviving Statistics

How the survivor bias distorts reality

When I purchased my latest vehicle, I was astonished to get the license plate 6NWL485. What are the chances that I would get that particular configuration? Before I received it, the odds were one in 175,760,000. (The number of letters in the alphabet to the power of the number of letters on the plate times the number of digits from 1 to 10 to the power of the number of digits on the plate: 26^3 x 10^4.) After the fact, however, the probability is one.

This is what Pomona College economist Gary Smith calls the "survivor bias," which he highlights as one of many statistically related cognitive biases in his deeply insightful book *Standard Deviations* (Overlook, 2014). Smith illustrates the effect with a playing card hand of three of clubs, eight of clubs, eight of diamonds, queen of hearts and ace of spades. The odds of that particular configuration are about three million to one, but Smith says, "After I look at the cards, the probability of having these five cards is 1, not 1 in 3 million."

The conclusion seems obvious once you think about it, but most of us are regularly fooled by the survivor bias. Consider the plethora of business books readily available in airport bookstalls that feature the most successful companies. Smith analyzes two of the best sellers in the genre. In his 2001 book *Good to Great* (more than three million copies sold), Jim Collins culled 11 companies out of 1,435 whose stock beat the market average over a 40-year time span and then searched for shared characteristics among them that he believed accounted for their success. Instead, Smith says, Collins should have started with a list of companies at the *beginning* of the test period and then used "plausible criteria to select eleven companies predicted to do better than the rest. These criteria must be applied in an objective way, without peeking at how the companies did over the next forty years. It is not fair or meaningful to predict which companies will do well after looking at which companies did well! Those are not predictions, just history." In fact, Smith notes, from 2001 through 2012 the stock of six of Collins's 11 "great" companies did worse than the overall stock market, meaning that this system of post hoc analysis is fundamentally flawed.

Smith found a similar problem with the 1982 book *In Search of Excellence* (more than three million copies sold), in which Tom Peters and Robert Waterman identified eight common attributes of 43 "excellent" companies. Since then, Smith points out, of the 35 companies with publicly traded stocks, 20 have done worse than the market average.

The survivor bias was evident in the reception of Walter Isaacson's 2011 best-selling biography of Steve Jobs, as readers scrambled to understand what made the mercurial genius so successful. Want to be the next Steve Jobs and create the next Apple Computer? Drop out of college and start a business with your buddies in the garage of your parents' home. How many people have followed the Jobs model and failed? Who knows? No one writes books about them and their unsuccessful companies. But venture capitalists (VCs) have data on the probability of a garage start-up becoming the Next Big Thing, and here the survivor bias is of a different sort.

David Cowan of Bessemer Venture Partners in Menlo Park, Calif., told me in an e-mail: "For garage-dwelling entrepreneurs to crack the 1% wealth threshold in America, their path almost always involves raising venture capital and then getting their start-up to an initial public offering (IPO) or a large acquisition by another company. If their garage is situated in Silicon Valley, they might get to pitch as many as 15 VCs, but VCs hear 200 pitches for every one we fund, so perhaps 1 in 13 start-ups get VC, and still they face long odds from there. According to figures that the National Venture Capital Association diligently collects through primary research and publishes on their Web site, last year was somewhat typical in that 1,334 start-ups got funded, but only 13% as many achieved an IPO (81 last year) or an acquisition large enough to warrant a public disclosure of the price (95 last year). So for every wealthy start-up founder, there are 100 other entrepreneurs who end up with only a cluttered garage."

Surviving those statistical odds is rare indeed. SA

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Illustration by Izhar Cohen

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 34 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

It's a Cookbook!

An argument for additional alimentary arthropods

The recipe for wild mushroom risotto starts with the ingredients list. The risotto includes rice, garlic, minced onion and vegetable stock. The mushroom mixture contains half a pound of wild mushrooms, garlic, butter, thyme, 12 grasshoppers with the legs and wings removed, and two thirds of a cup of buffalo worms, along with salt and freshly ground black pepper. Julia Child has left the building.

Entering the building are Arnold van Huis and Marcel Dicke, entomologists at Wageningen University in the Netherlands, along with chef Henk van Gurp, from the nearby Rijn IJssel Vakschool, which teaches hotel and tourism management. The wild mushroom risotto recipe is one of 32 in the frying Dutchmen's new volume, *The Insect Cookbook: Food for a Sustainable Planet*.

Americans may involuntarily utter "Gurp" as they contemplate dishes rich in grasshoppers and buffalo worms, the larvae of a rather handsome beetle. Therefore, the meat of the book is its essays discussing the value of incorporating insects into culinary cultures that have mostly eschewed them.

More than 1,900 insect species are on the menu in great swaths of the world. "People in Asia, Africa and Latin America do commonly eat insects," the authors say, "not because of hunger, but because they are considered special treats." Indeed, insects in these regions can be more expensive than meat. The authors note that an analogous situation exists in Europe, where meat can be less pricey than shrimp. And shrimp, being fellow arthropods, are much closer morphologically, but for some reason not yuckitudinally, to insects than to cows or chickens.

Of course, Americans already eat plenty of insects. "Apples sometimes have an insect or two in them—and these just get ground up … and become part of the applesauce and juice," the authors point out. "The same goes for tomatoes and ketchup, grains and bread, coffee beans and coffee, and a long list of other foods." The most healthful ingredients in your burger and side of fries may be the insect bits in the bun and ketchup.

The U.S. has legal limits, say Dicke and the two vans: "The maximum is sixty insect pieces per 3.5 ounces … of chocolate, thirty insect pieces per 3.5 ounces of peanut butter, and five fruit [fly eggs] per 1 cup … of fruit juice. Calculations indicate that each of us unknowingly consumes about 1 pound … of insects per year."

And that does not include any foodstuffs such as red candy or strawberry yogurt that contain the dye carmine. This red additive comes from the smashed bodies of a scale insect called the cochineal. In 2012 news of the presence of carmine in six Starbucks offerings quickly got the coffee giant to switch to a tomato-derived replacement dye. Personally, I'd keep the carmine and get rid of almost everything else in the products, which included the raspberry swirl cake, the mini doughnut with pink icing and the red velvet whoopie pie.

The push to increase the attraction of insects as food for people comes from two population figures. First, the human population of the planet is expected to reach nine billion by the middle of this century. Second, the population of insects may be as high as 10 quintillion. The authors put that stat in what may seem to be more accessible terms but is still perhaps merely mind-blowing: "For every human being on Earth, there are between 200 million and 2 billion insects." Put down the spray gun, you're surrounded.

Those nine billion people will need protein, and cultivating insects is far more efficient than producing other animal foods, especially beef, in terms of land and water use and the feed-to-food conversion ratio: about two pounds of feed will get you a pound of edible crickets, compared with 25 pounds of feed for a pound of beef. If we want a comeback of small farmers, it may be through farming these small critters.

So, as *The Insect Cookbook* recommends, think of grasshoppers as land shrimp. Call locusts sky prawns. Frenchifying it to a bonbon *sauterelle* could help the grasshopper bonbon hop off shelves. As my, and seemingly everybody else's, mother used to say upon the discovery of an insect in our food, "It's just a little extra protein." SA

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Illustration by Matt Collins

Innovation and discovery as chronicled in *Scientific American*

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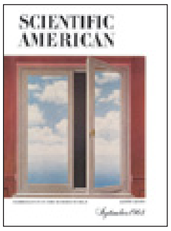


September 1964

Quanta of Space

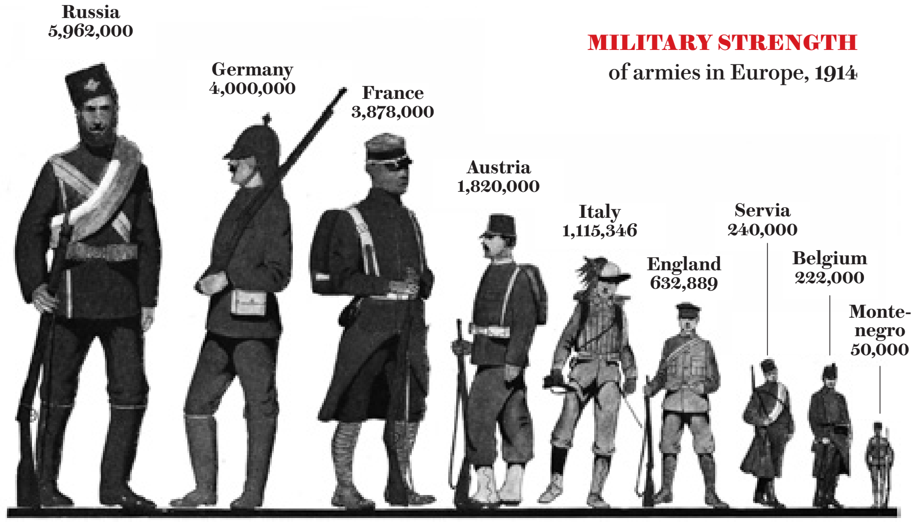
"In the theory of relativity, one of the two most notable scientific advances of this century (quantum theory is the other), the gravitational effect of gross matter has been reduced to geometry. Just as the geometry of a mountainous region requires a distance formula that varies from place to place to represent the varying shape of the land, so Einstein's geometry has a variable distance formula to represent the different masses in space. Matter determines the geometry, and the geometry as a result accounts for phenomena previously ascribed to gravitation. Geometry has ingested part of reality and may have to ingest all of it. Today in quantum mechanics physicists are striving to resolve the seemingly contradictory wave and particle properties of subatomic matter, and they may have to generate both from quanta of space. Perhaps matter itself will also dissolve into pure space.—Morris Kline"

September 1914

The Great War

"To appreciate the stupendous character of the War of the Nations which is now in full swing on the continent of Europe, we must bear in mind two facts: first, that it is a war to the death; second, that in the full realization of the absolute finality of the result, every one of the contending nations has already called out or has stated that it will do so, the whole of its trained reserve, thus putting some sixteen millions of men under arms. In the interests of humanity it is better that the nations which go down in absolute defeat should realize that the verdict is one against which there is no appeal."

For a slide show on military science from World War I, see www.ScientificAmerican/sep2014/wwi



SCIENTIFIC AMERICAN, VOL. CXI, NO. 10; SEPTEMBER 5, 1914

Another View of War

"People are so suspicious about wars nowadays. One wonders even if patriotism isn't rather stupid. One has the preliminary thrill; there is flag-wagging, the blast of a trumpet, the glorious traditions of the Fatherland, and then this vague but persistent vision of a fat, beady-eyed financier lurking in the background. We have been sold so many times, one becomes wary. One could fight wholeheartedly in a war for the end of war, but in no other sort of war whatever."

Jupiter's Moon

"An announcement of much interest comes in a recent telegram from Prof. Tucker, who is at present acting director of the Lick Observatory. On July 21st, Mr. Nicholson, at that observatory, photographed a faint object in the vicinity of Jupiter, near the eighth satellite, but still fainter. Further observations have been secured, and the telegram states that the calculation of the orbit of the newly discovered body proves it to be a satellite of the great planet—the ninth to be discovered. This tiny body, however, is so faint that it must be near the limit of visibility, if not beyond it, in the greatest telescopes, and it can only be observed photographically."

It was not until 1975 that the ninth of Jupiter's 67 known moons was named Sinope.

September 1864

Down with Housework

"When Charles Dickens wrote 'Bleak House' he created a prominent character: Mrs. Jellaby. This lady had a mission. She was obliged to look after the heathen, and she looked after them so fast and so far that her own children were in rags and tatters; her house was a scene of disorder. This was simply the natural result of neglecting her duty. But if the same distinguished author should revisit this country and write about ladies with missions, he would find a very different state of things to chronicle. Look at what the simple machinery of the household has done for society. Years ago the housewife sat of an evening and plied her needle when the heavier labors of the day were done. The garments that rose before her aching sight threatened to overwhelm her. It is not so now, and we may thank inventors that have provided machines to do the drudgery of the needle."

A Great Piece of Fish

"The first salmon caught in the Connecticut River for forty years was taken at Chicopee the other day, and served at the Massasoit House, Springfield, Mass."

The 1 Percent Difference

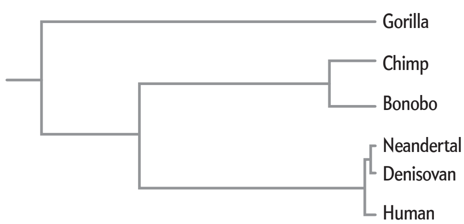
Genome comparisons reveal the DNA that distinguishes *Homo sapiens* from its kin

In 1871 Charles Darwin surmised that humans were evolutionarily closer to the African apes than to any other species alive. The recent sequencing of the gorilla, chimpanzee and bonobo genomes confirms that supposition and provides a clearer view of how we are connected: chimps and bonobos in particular take pride of place as our nearest living relatives, sharing approximately 99 percent of our DNA, with gorillas trailing at 98 percent.

Yet that tiny portion of unshared DNA makes a world of difference: it gives us, for instance, our bipedal stance and the ability to plan missions to Mars. Scientists do not yet know how most of the DNA that is uniquely ours affects gene function. But they can conduct whole-genome analyses—with intriguing results. For example, comparing the 33 percent of our genome that codes for proteins with our relatives' genomes reveals that although the sum total of our genetic differences is small, the individual differences pervade the genome, affecting each of our chromosomes in numerous ways. *—Kate Wong*

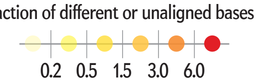
SCIENTIFIC AMERICAN ONLINE
For more genome comparisons, see ScientificAmerican.com/sep2014/graphic-science

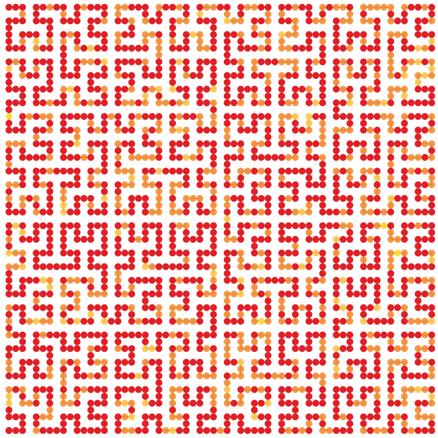
Family tree

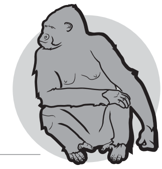


Each dot represents a sequence of about 500,000 pairs of chemical bases—the A, T, C and G of our genetic code—in the protein-coding portion of the human genome in the order that they appear on our chromosomes.

The color of the dot indicates how well the human sequence matches up with the corresponding sequence in the comparison species, with red signifying a greater difference between the two.

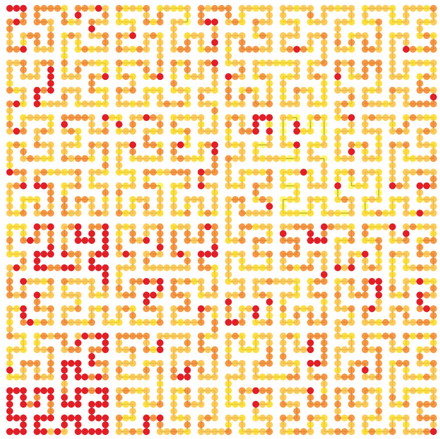






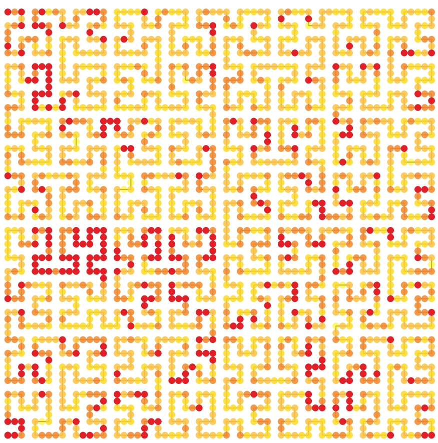
Gorilla

On the whole, our coding genome differs more from the gorilla's than from the chimp's or the bonobo's, reflecting the fact that we have been evolving along separate trajectories for a longer period. But about 15 percent of the human genome looks more like the gorilla's than the chimp's or the bonobo's.



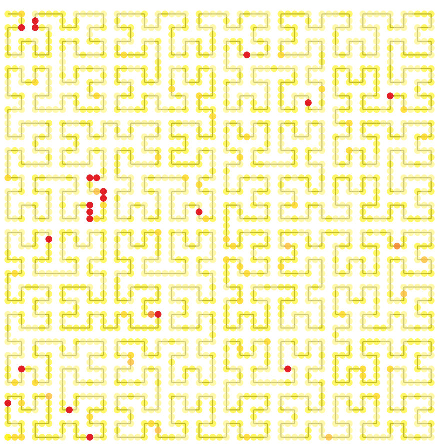
Chimp

Researchers have traditionally considered the chimpanzee, which lives in patriarchal societies, to be our closest living relative and thus the best model for reconstructing the lives of ancient human ancestors. The recent genome-sequencing work calls that view into question, however.



Bonobo

The genome of the bonobo—which has a social structure centered on females—shows it to be just as closely related to us as chimps are, although we differ from the two species in distinctive ways. These findings may force scientists to reconsider how our long-ago forerunners lived.



Denisovan

The Denisovans—a group of archaic humans closely related to the Neandertals—show far fewer sequence differences from us than any of the African apes do, having shared a common ancestor with *H. sapiens* in the much more recent past, around 400,000 years ago.

SOURCES: UNIVERSITY OF CALIFORNIA, SANTA CRUZ, GENOME BROWSER (*chimp, gorilla and bonobo data*); MAX PLANCK SOCIETY (*Denisovan data*); "INITIAL SEQUENCE OF THE CHIMPANZEE GENOME AND COMPARISON WITH THE HUMAN GENOME," BY CHIMPANZEE SEQUENCING AND ANALYSIS CONSORTIUM, IN *NATURE,* VOL. 437; SEPTEMBER 1, 2005; "INSIGHTS INTO HOMINID EVOLUTION FROM THE GORILLA GENOME SEQUENCE," BY AYLWYN SCALLY ET AL., IN *NATURE,* VOL. 483; MARCH 8, 2012; "THE BONOBO GENOME COMPARED WITH THE CHIMPANZEE AND HUMAN GENOMES," BY KAY PRÜFER ET AL., IN *NATURE,* VOL. 486; JUNE 28, 2012; "A HIGH-COVERAGE GENOME SEQUENCE FROM AN ARCHAIC DENISOVAN INDIVIDUAL," BY MATTHIAS MEYER ET AL., IN *SCIENCE,* VOL. 338; OCTOBER 12, 2012

Graphic by Martin Krzywinski, Illustrations by Portia Sloan Rollings


A taco truck
in the other
blind spot.
An ambulance
racing by you.
An ice cream
truck in one
blind spot.
An ambulance
chaser, chasing
the ambulance.
It's 360 degrees of chaos out there. Be prepared.
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